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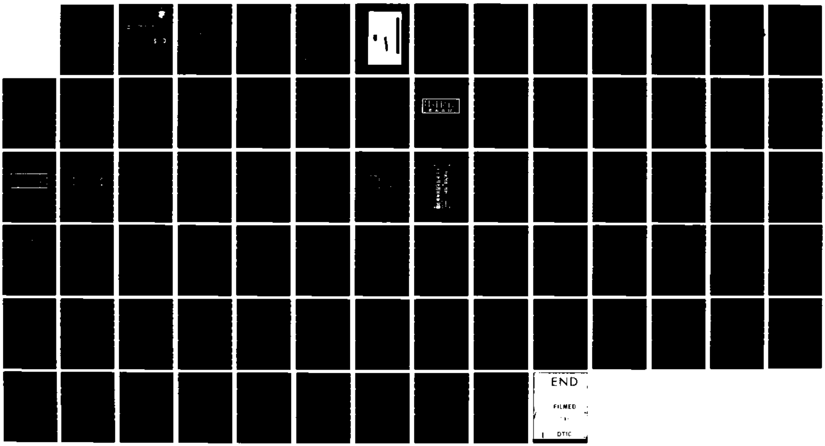

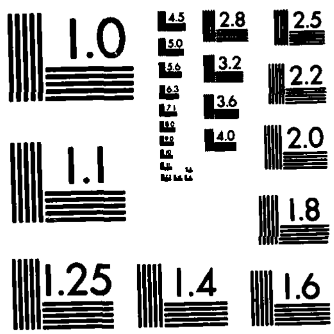

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RADC-TR-82-285
In-House Report
November 1982

FIBER OPTIC TRANCEIVER THERMAL ANALYSIS

Seymour F. Morris and Douglas J. Holzhauer

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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This report documents the thermal analysis done by the Systems Engineering Section in support of the in-house Air Support Operations Center (ASOC) Fiber Optic Remoting Project. The purpose of the ASOC project was to develop a fiber optic transceiver that would allow ASOC systems to replace the 26 pair metallic cable with the much lighter dual fiber optic cable. In support of this project, RBES used computer aided thermal analysis and laboratory thermal measurement to design and verify the thermal design of

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the ASOC experimental module.

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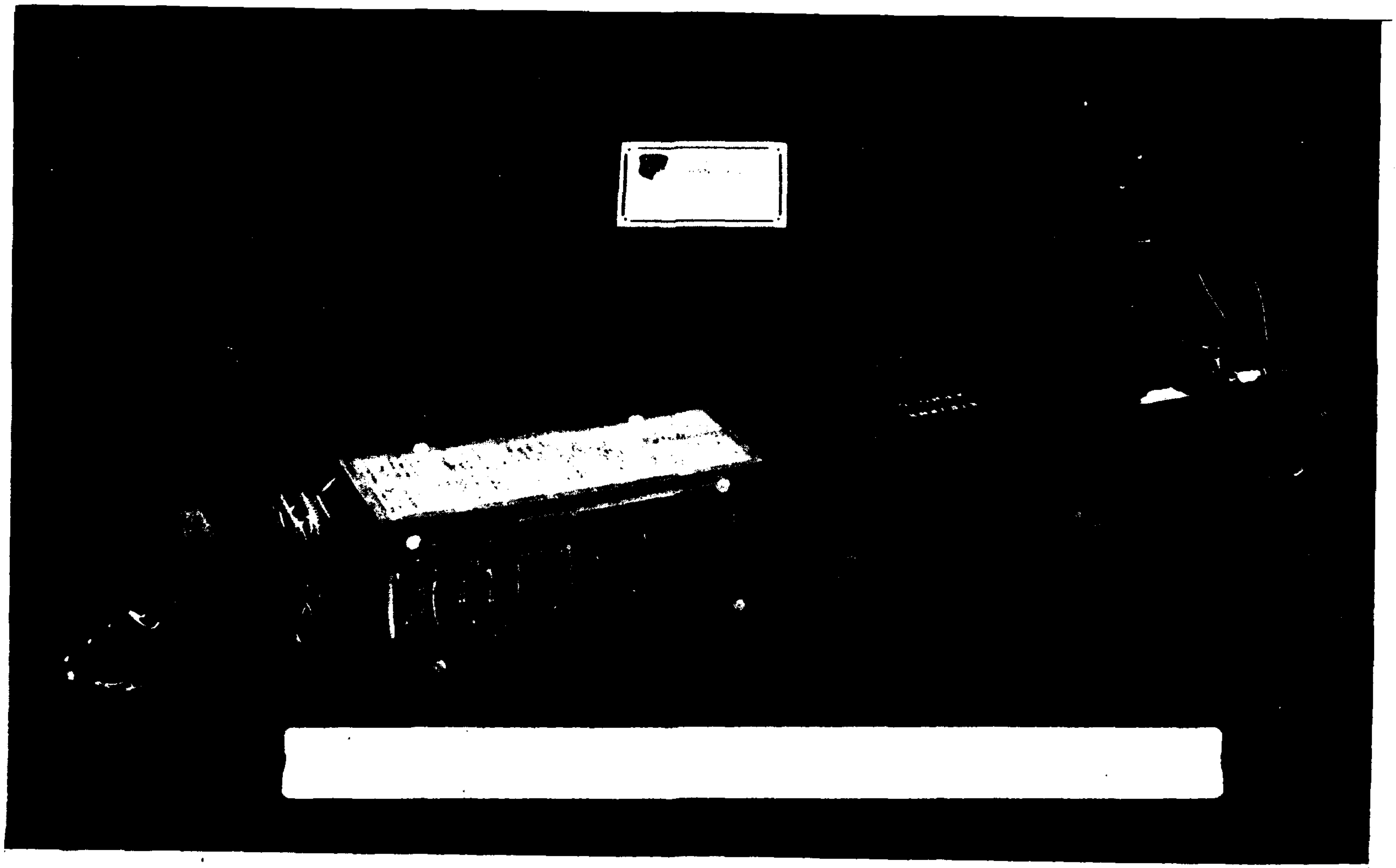

AOSC FIBER OPTIC TRANSCEIVER

PREFACE

This report describes the main portion of the mechanical engineering support furnished to the Air Support Operations Center (ASOC) Fiber Optic Remoting Project. The ASOC project was an RADC in-house program to design a tactical fiber optic communication link to replace the conventional metallic cables. The work that is reported here consists of the computer assisted thermal analysis and design and the laboratory temperature measurement of the electronics contained in the ASOC fiber optic transceiver. The thermal analysis was made by modeling the ASOC module and then using the Systems Improved Numerical Differencing Analyzer (SINDA) thermal analyzer computer program to calculate the component temperatures. The temperature measurement was made using thermocouples and a Hewlett Packard data acquisition system. In addition to the work that is reported here, a temperature measurement of the operating ASOC power supply and a reliability demonstration of the ASOC module were made in support of the ASOC project. The ASOC thermal design and laboratory measurement was performed between September 1980 and February 1982. Mr. Seymour Morris was employed by RADC under the Summer Engineering Aid Program during the summer of 1981. The authors also wish to acknowledge the work performed by Mr. John Carbone (RADC/RBE-1) on this project. This included a considerable amount of laboratory thermal measurement work as well as assistance in running the thermal model on the computer.

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I INTRODUCTION

The Air Support Operations Centers (ASOC) deployed in support of the North Atlantic Treaty Organization (NATO) operate under a severe weight constraint in order to maintain a highly mobile posture. A continuing problem in this area is the weight and volume of the electrical cable that is required by the communication systems in the ASOCs. A fiber optic communication system is currently being developed at RADC to reduce the weight and volume of the system. Two electrical/optical transceivers connected by a dual fiber optic cable can directly replace the 26-pairmetallic cable that is presently being used for communications between stations. The new fiber optic system (Fig 1) will have the following advantages over the old system:

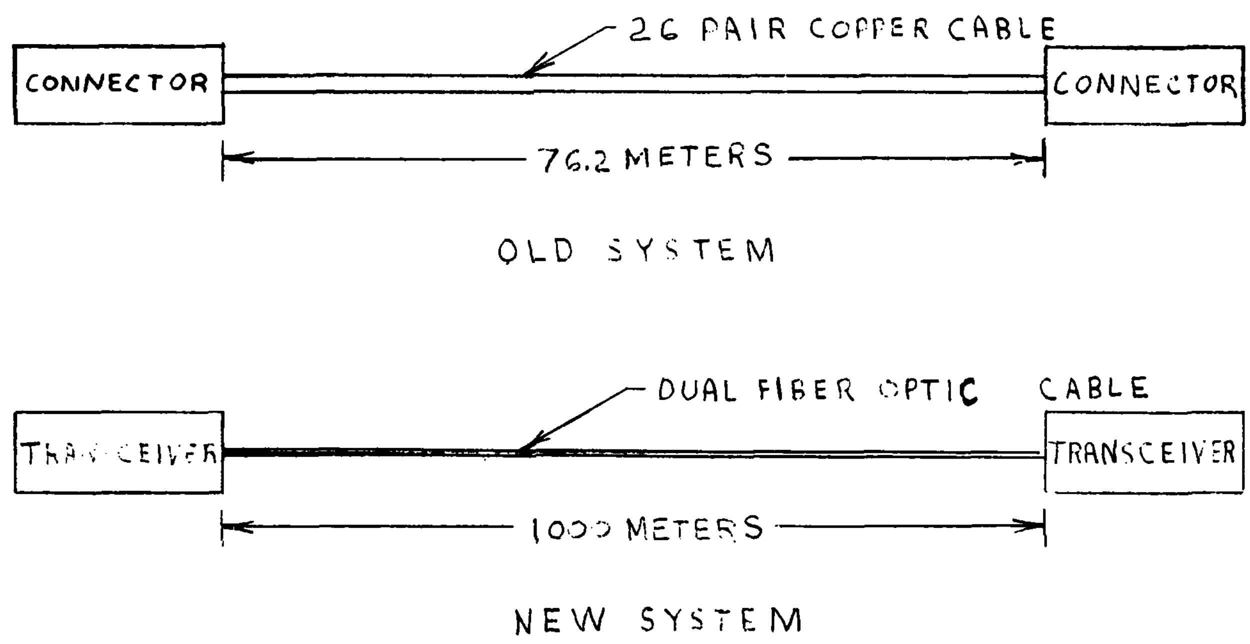
a. A 75% reduction in weight and volume.

b. Improved transmission performance.

c. Longer lengths of cable on each reel, thus allowing for increased distances between stations which will increase survivability and improve operational flexibility.

d. The elimination of ground loops, cross talk, electromagnetic interference, and electromagnetic pulse associated with the use of metallic conductors.

The trend in military electronic equipment has been to make systems as compact as possible for ease of installation and transportation. Compactness leads to high component density which, in turn, may lead to excessive component temperatures. Since inadequate cooling is a primary cause of poor reliability in military electronic equipment, a thermal analysis was performed on the ASOC transceiver unit to increase component reliability. Desired performance and reliability levels can only be accomplished if the electronic, thermal and mechanical designs are all well executed and carefully integrated. Because of a time limitation, these designs were not integrated sufficiently to achieve an optimized thermal design. The transceiver case dimensions were specified by ASOC early in the development stages so that existing connectors on the sides of the shelters could be used. Also the electronic design could not easily be changed to accommodate more efficient heat sinks.



The new Fiber Optic System greatly increases the separation distance between transceivers with the use of thin plastic cable to carry light waves.

FIGURE 1

ASOC SEPARATION DISTANCE

II COOLING METHODS

Conduction and convection cooling are the two methods used to cool the ASOC transceiver unit.

Conduction cooling involves the transfer of kinetic energy from one molecule to another. Conductive heat transfer occurs in all solid materials and may also occur through air if the air space between the two surfaces is less than ¼ inch. But because of its high thermal resistance, the amount of heat transferred through air is very small. Conduction is the primary method used to transfer heat from the heat producing components to the outside of the transceiver case. This is usually accomplished by fastening a copper heat sink to the frame and then making a contact between the heat sink and the heat producing component.

Convection is the transfer of heat from the surface of a solid to a moving mass of fluid, either a gas or a liquid. This mode of heat transfer is brought about through a change of density of the air when it warms. The change of density makes the air rise and dissipates the heat. This is the method used to transfer heat from the transceiver case to the ambient air.

III ANALYSIS METHOD

1. Thermal Terms

A thermal network has many similarities to an electrical one as listed below:

THERMAL	ELECTRICAL	THERMAL DEFINITION
Temperature	Voltage	The potential that causes heat to flow from hotter areas to cooler ones. (temperature difference)
Heat Flux	Electrical Current	The power that an electrical component dissipates.
Thermal Resistance	Electrical Resistance	The resistance to heat flow from one point to another.

Thermal Conductance	Electrical Conductance	The ability to conduct heat from one point to another.
Ultimate Heat Sink	Ground	This is the ambient air around the transceiver unit.

2. Kirchhoff's Laws for a Thermal Network

Kirchhoff's laws may be applied once a steady state condition has been reached in the thermal circuit. Kirchhoff's laws for a thermal circuit are:

a. The sum of all the heat arriving at any junction in a circuit is equal to the sum of all the heat leaving that junction.
b. Around any closed loop, the sum of the temperature rises is equal to the sum of the temperature drops.

When Kirchhoff's laws are applied to anything but the smallest of thermal circuits, the resulting simultaneous equations need to be solved with the aid of a computer.

3. Network Analysis

The Systems Improved Numerical Differencing Analyzer (SINDA) is a computer program that is designed to handle lumped parameter thermal analysis problems that are represented in an electrical analogy. This program allows a maximum of 16,383 nodes to be defined in any single problem. Four types of data must be input to the program. They are the node, source and conductor data along with the initial temperatures of the nodes. The program will then apply Kirchhoff's laws from this data and solve the resulting equations for the node temperatures.

Node data consists of the node number, initial temperature of the node, and the type of node. Three node types are possible. Each node type is listed below along with its specific properties:

(1) Diffusion - Has thermal capacitance and can store energy.
(2) Arithmetic - Has zero thermal capacitance.
(3) Boundary - Has a constant temperature.

The source data consists of the node number and heat output (wattage) of that node.

The conductor data input consists of an assigned conductor number, the node numbers that the conductor is connected to, and the conductance value for the conductor. The conductance value for a conductor is the reciprocal of the thermal resistance between the two nodes.

Node numbers are assigned any time there is a significant thermal resistance and a temperature difference between one location and another.

IV METHODS OF CALCULATING THERMAL RESISTANCE

There are three types of thermal resistances that occur in the ASOC transceiver unit. They are conductive, convective and contact resistance.

The equation used to calculate the thermal resistance (R) for conduction cooling is given by Equation 1. The units of resistance are $\frac{^oC}{watt}$.

$$R = \frac{x}{KA} \qquad \text{(Equation 1)}$$

where:
- x - is the length between nodes. (in)
- A - is the cross sectional area through which the heat is flowing. (in^2)
- K - is the thermal conductivity of the substance through which the heat is flowing. The units of thermal conductivity are $\frac{watt}{in\,^oC}$.

Natural convection for vertical flat plates, as we have on the outside of the case, depends on the coefficient of heat transfer h_c. For natural convection, the variable h_c defines the thermal characteristics of the air film which clings to the plate and restricts the flow of heat from the plate to the ambient air. The empirical equation for calculating h_c is given by Equation 2, and the units of h_c are $\frac{watt}{^oC\ in^2}$.

$$h_c = 1.062 \times 10^{-3} \, (T/L)^{0.25} \qquad \text{(Equation 2)} \qquad \text{(Ref 1)}$$

where: T - is the temperature difference (^oC) between the ambient air and the vertical flat plate.

L - is the vertical height of the flat plate measured in feet.

The equation used to calculate the thermal resistance for convection cooling is given by Equation 3.

$$R = \frac{1}{h_c A} \qquad \text{(Equation 3)}$$

where: A - is the surface area of the flat plate. (in^2)

h_c - is the coefficient of heat transfer. For natural convection, it is calculated using Equation 2. It has units of $\frac{\text{watts}}{in^2 \, ^oC}$.

A third type of thermal resistance is contact resistance. This occurs when two materials are in direct contact with each other with no other substance such as thermal grease in between. Contact resistance is really a type of conduction resistance and is a function of the types of materials in contact, the contact pressure, and the contact area.

The equation used to calculate the thermal resistance for two materials in direct contact is given by Equation 4.

$$R = \frac{1}{h_c A} \qquad \text{(Equation 4)}$$

where: A - is the contact area. (in^2)

h_c - is the coefficient of heat transfer. For contact resistance, its value can be found in heat transfer handbooks. It has units of $\frac{\text{watt}}{in^2 \, ^oC}$.

The temperature outputs from the SINDA Program were examined for temperatures that would exceed component specifications. If temperature specifications were exceeded, then a new heat sinking design was specified, and revised thermal conductance data was input into the SINDA Program. The program was then rerun and a new temperature profile was obtained.

After arbitrary node numbers were assigned to the points of interest, they were connected into a circuit with the thermal resistances inserted between them as shown in Fig 2a - 2c.

V CALCULATING THE THERMAL RESISTANCES

1. PULSE CODE MODULATOR (PCM)

The three PCM boards mounted on the left side of the transceiver will be considered first (Fig 6). They each have eight Integrated Circuits (IC's) mounted on them as shown in Fig 3. The IC's that are assigned Node numbers 60-63 are taller than the IC's with Node numbers 64-67. For maximum heat transfer, all IC's should come in contact with the heat sink; however, because of manufacturing difficulties, the copper heat sink can only be made so it contacts the taller IC's and leaves an air gap between the smaller IC's as shown in Fig 4. The thermal resistance between the taller IC's (Nodes 60-63) and their heat sink (Node 121) is calculated using Equation 1.

The thermal resistance between Nodes 60-63 and Node 121 is:

$$R = \frac{x}{KA}$$

$$x = .02 \text{ in}$$

$$K_{air} = .00075 \frac{\text{watt}}{\text{in}^{o}\text{C}}$$

$$A = 1.15" \times .48" = .55\text{in}^2$$

$$R = \frac{.02}{.00075(.55)} = 48.49 \frac{^{o}\text{C}}{\text{watt}}$$

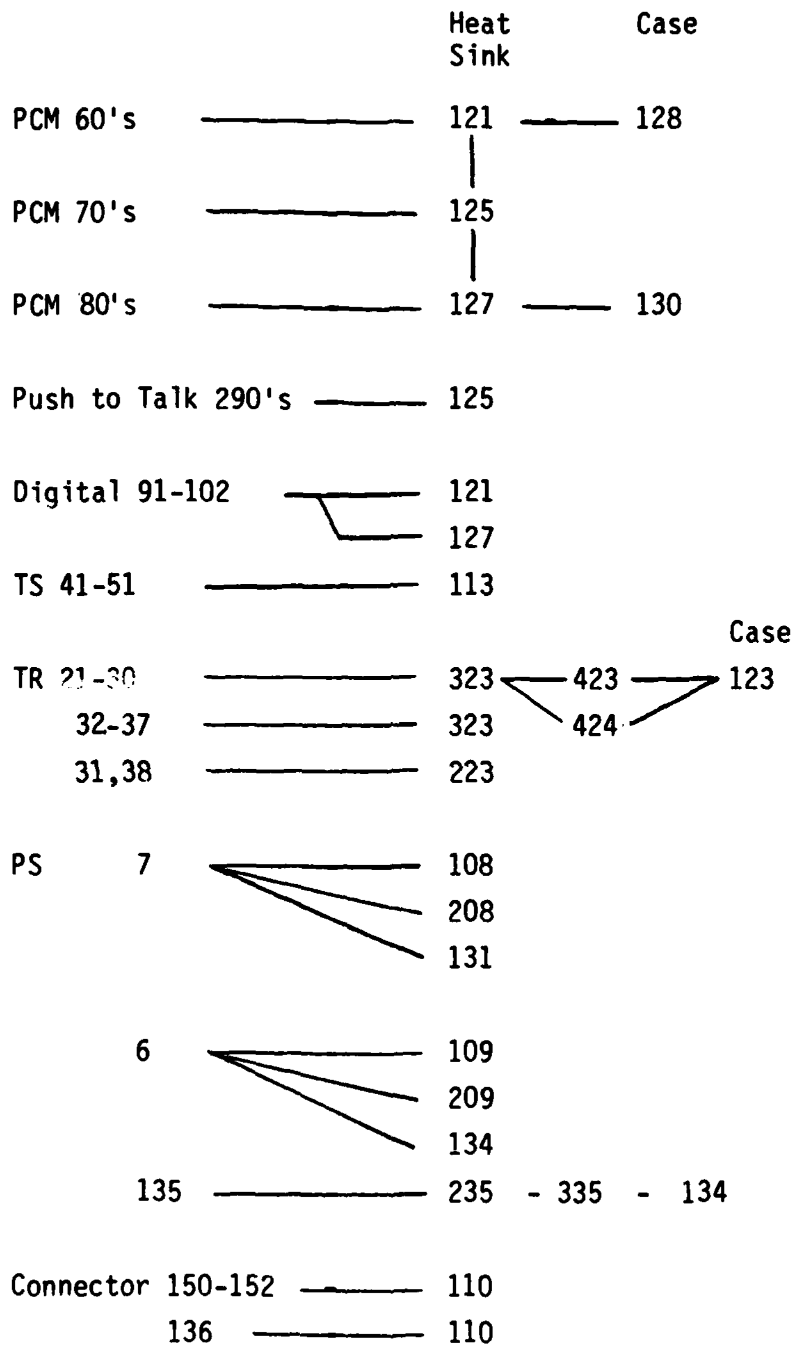


FIGURE 2a

PRINTED CIRCUIT BOARD NODES

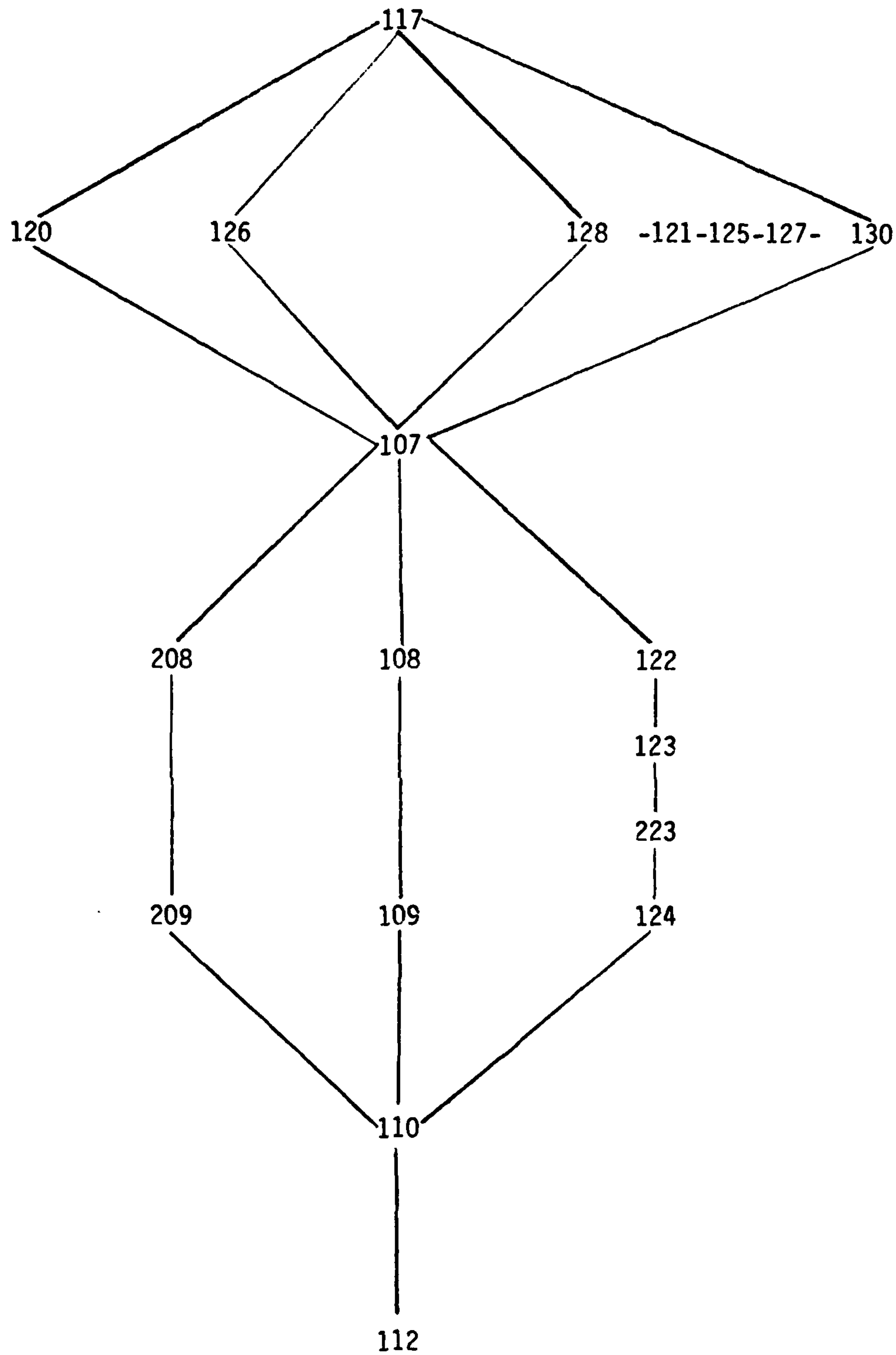


FIGURE 2b

INNER CHASSIS NODES

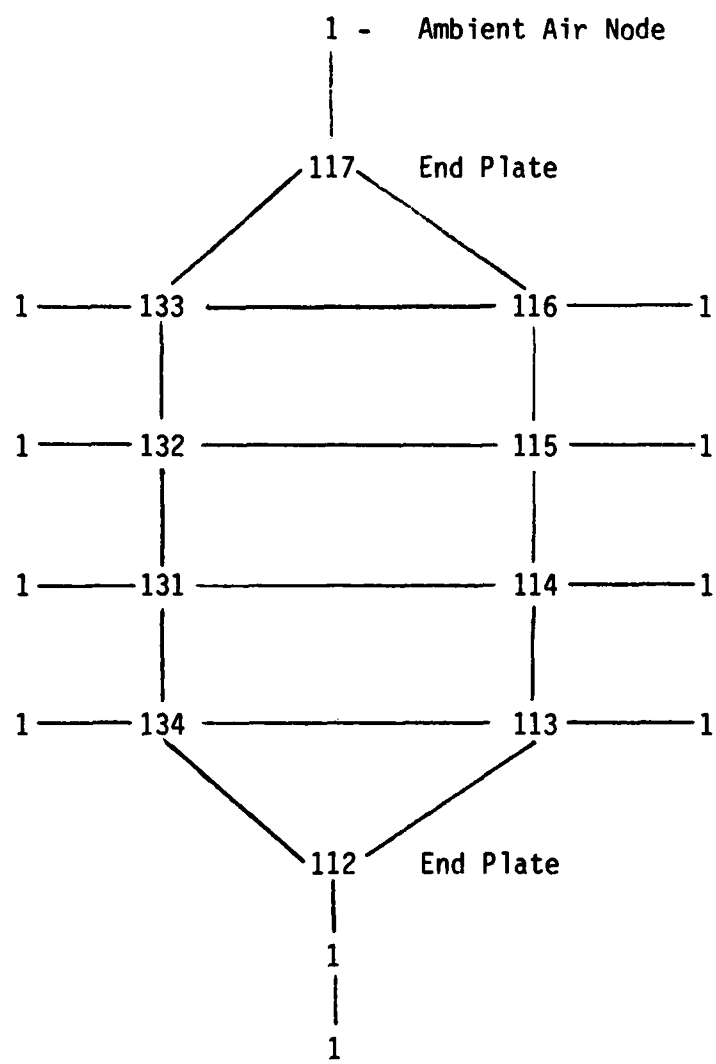


FIGURE 2c

CASE EXTERIOR NODES

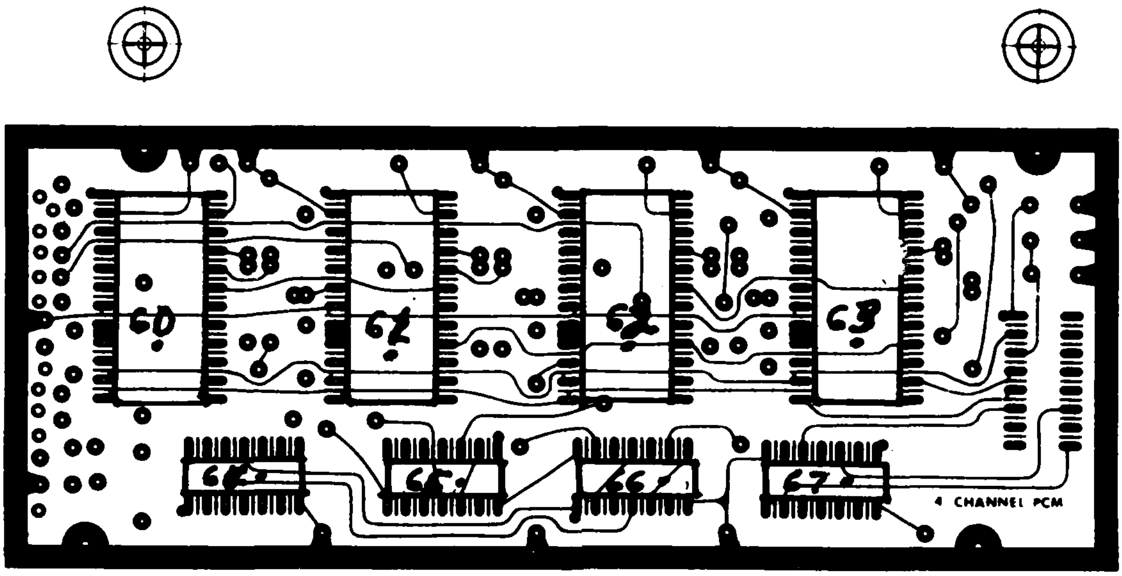
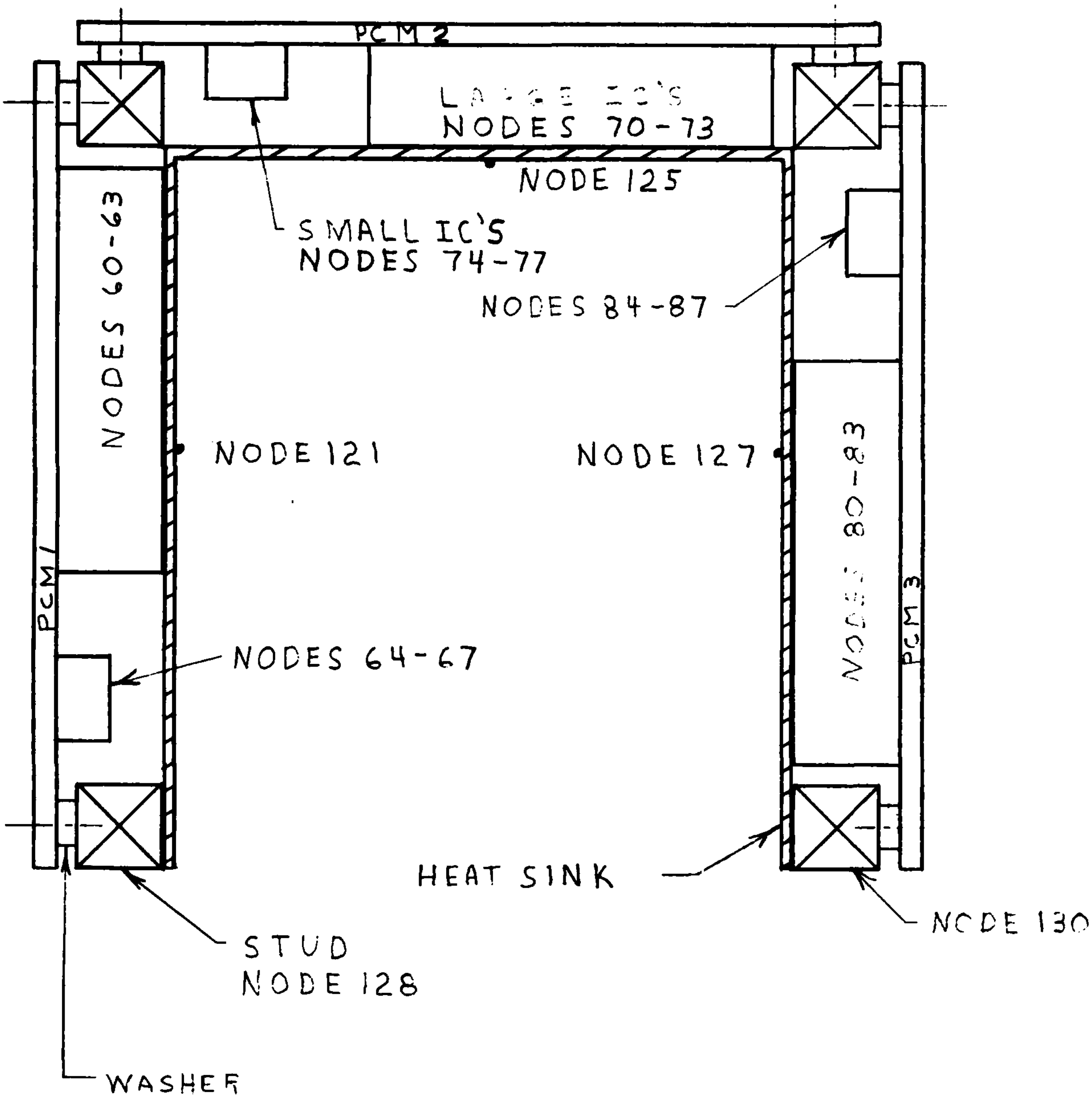


FIGURE 3

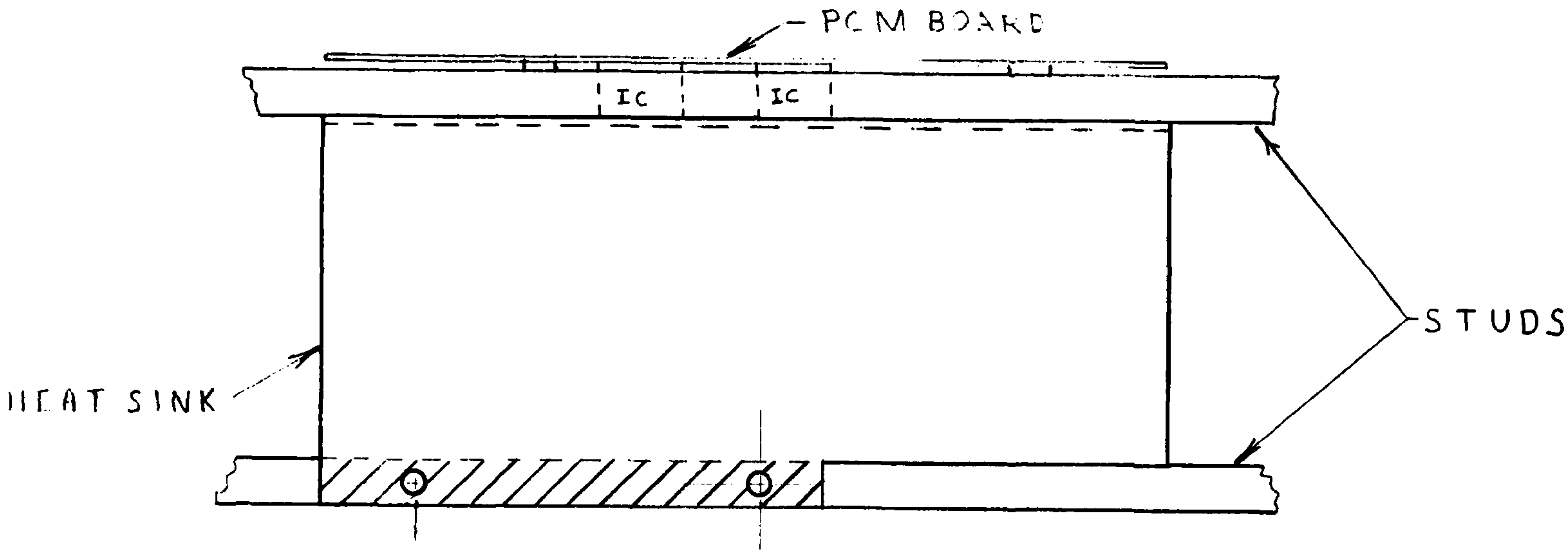
PCM BOARD



The three PCM boards are mounted to the framing studs with nylon washers as shown above. The heat sink channel contacts the four large IC's but leaves a 5/16" air gap between the four smaller IC's.

FIGURE 4

PCM BOARD HEAT SINK - CROSS SECTION



This shows a side view of the PCM heat sink. The cross-hatched area represents the contact surface between the heat sink and the framing studs.

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FIGURE 5

PCM BOARD HEAT SINK

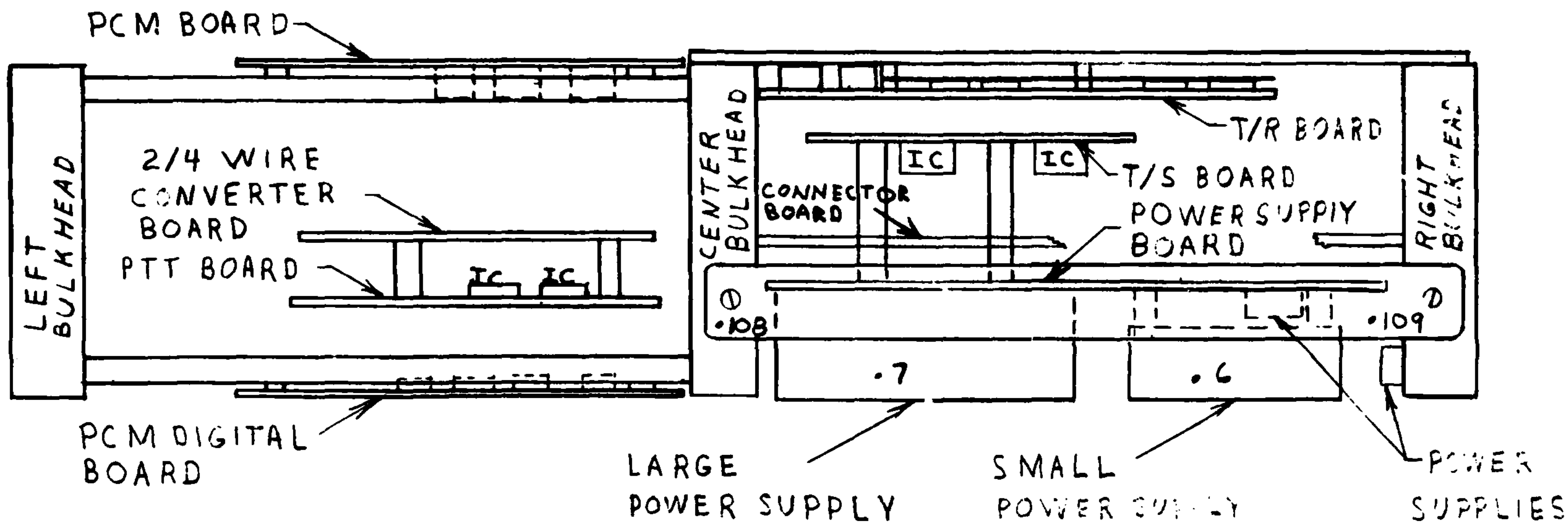


FIGURE 6
CIRCUIT BOARD LOCATIONS

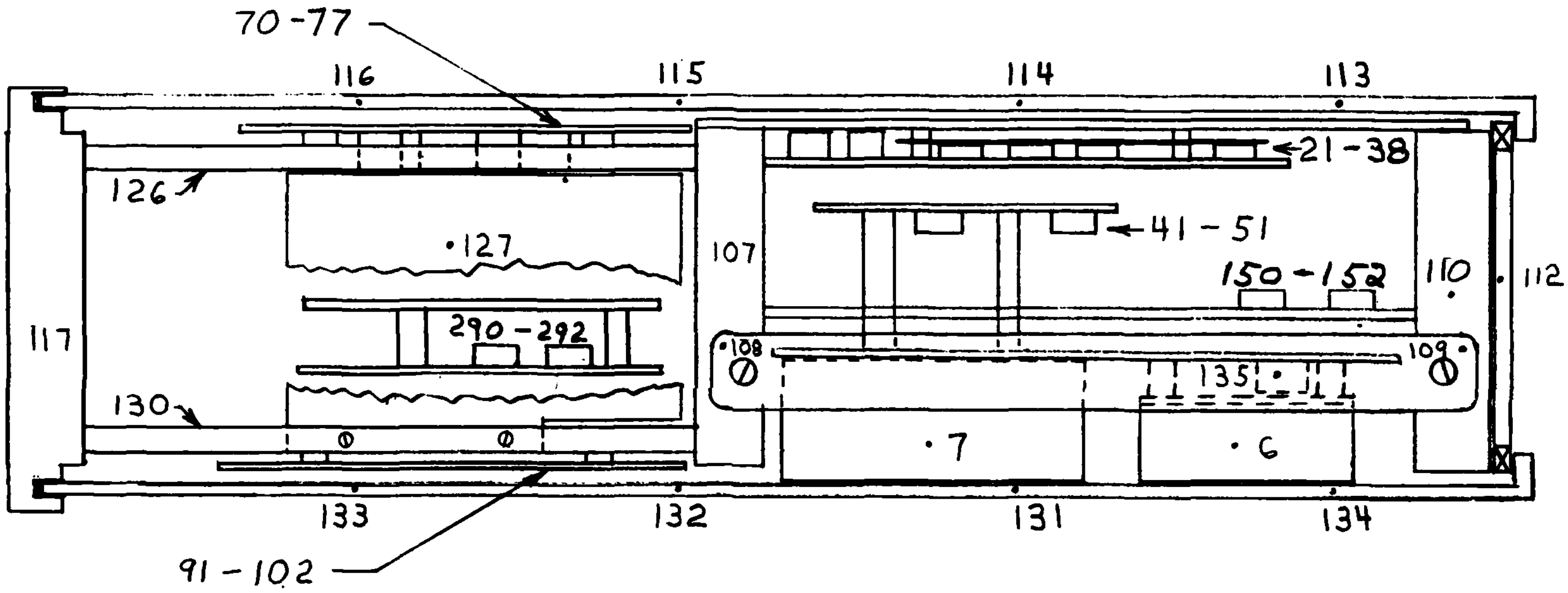


FIGURE 7

KEY NODE LOCATIONS

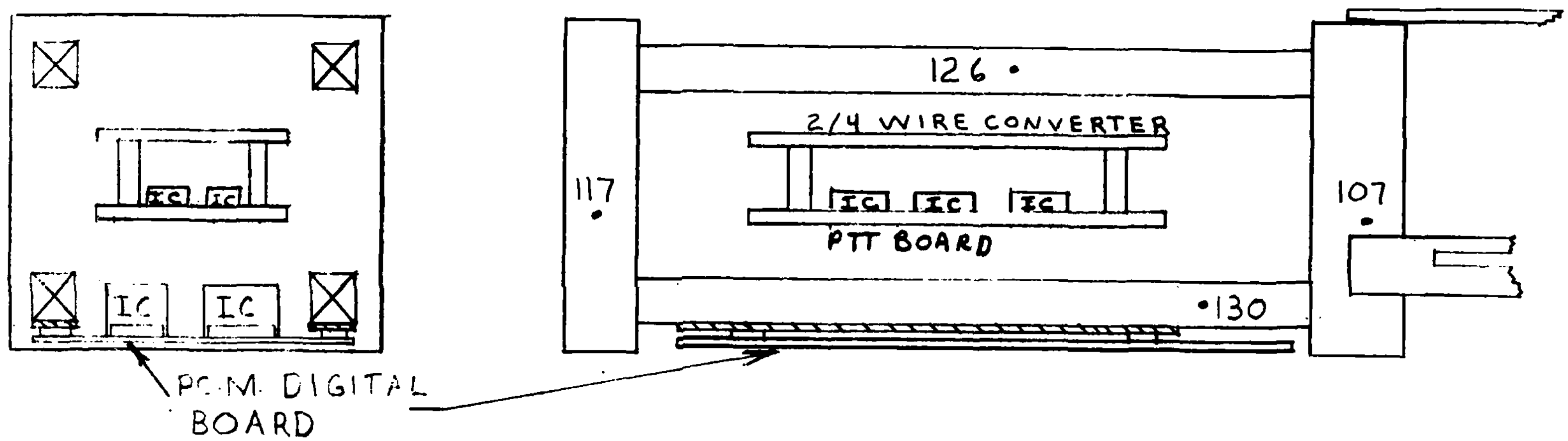


FIGURE 8

PCM/PUSH TO TALK HEAT SINKS

The heat transfer between the smaller IC's (Nodes 64-67) and their heat sink (Node 121) is also considered as conductive heat transfer. This is because a minimum of ¼ inch between the IC and heat sink is required for substantial convection to take place. Our clearance is 5/32 inch (Fig 4); thus, we treat air as the conductive material and use Equation 1.

The thermal resistance between Nodes 64-67 and Node 121 is:

$$R = \frac{x}{KA}$$

$x = 5/32$ in (measured)

$K_{air} = .00075 \frac{\text{watt}}{\text{in}^{o}\text{C}}$ (Ref 1b)

$A = .75" \times .25" = .188 \text{in}^2$

$$R = \frac{5/32}{(.00075)(.188)} = 1108.16 \frac{^{o}\text{C}}{\text{watt}}$$

Since there are three identical PCM boards with identical heat sinking, the resistance calculations for the other two are the same as above.

2. PCM Digital/Push to Talk

Because of space constraints, the PCM digital and the push to talk board rely on conduction through the air for cooling. The design is poor, at best, and was utilized here only because of the experimental nature of the unit. The push to talk board is facing the PCM heat sink (Node 125) and will conduct its heat there.

The thermal resistance between Nodes 290-292 and Node 125 is:

$x = .25$ in.

$K_{air} = .00075 \frac{\text{watt}}{^{o}\text{C in}}$

$A = .75" \times .25" = .18 \text{in}^2$

$$R = \frac{.25}{.00075(.18)} = 1852 \frac{^{o}\text{C}}{\text{watt}}$$

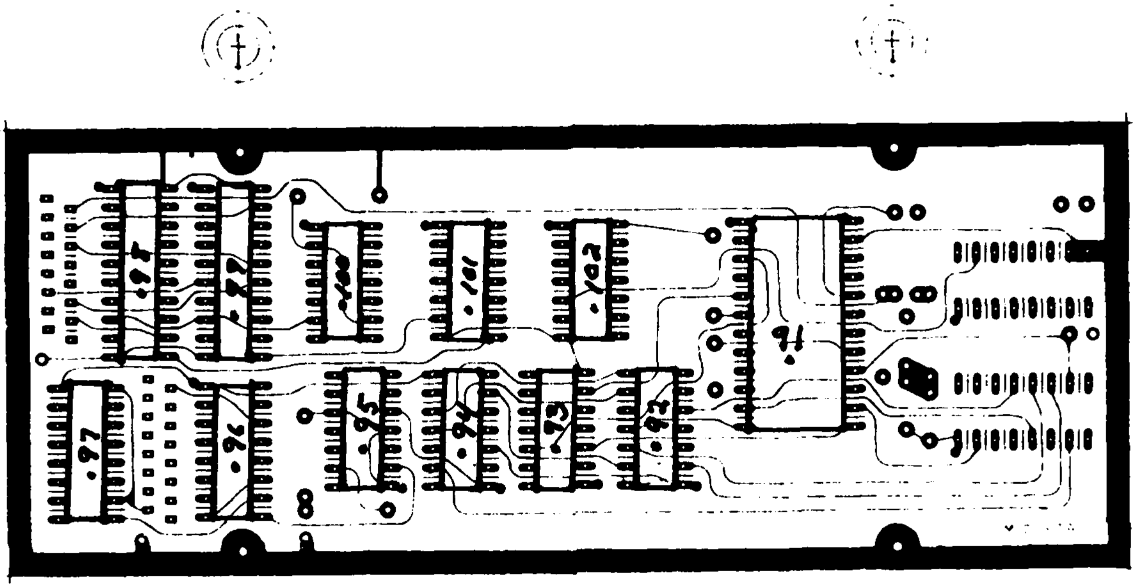


FIGURE 9

PCM DIGITAL BOARD

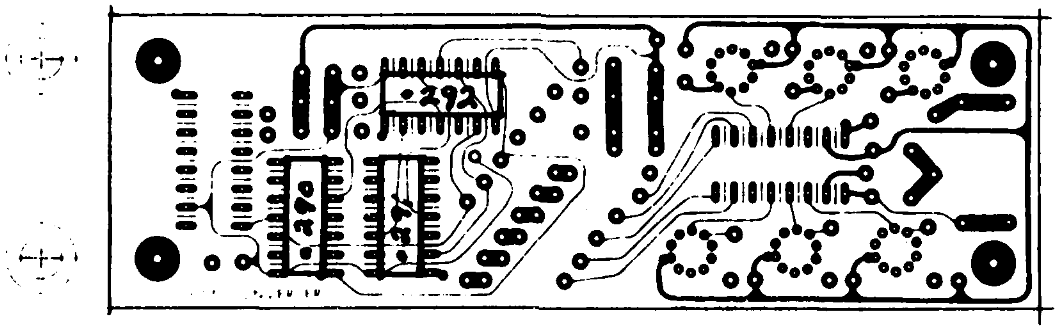


FIGURE 10

PTT CONVERTER

The thermal path for the heat flow from the IC's on the PCM digital board will be an approximation since the actual path is very complicated. For this approximation, it will be assumed that heat flows from each IC to both Nodes 121 and 127, which are both on the sides of the PCM heat sink.

The thermal resistance between IC's (Nodes 91-102) and Nodes 121, 127 is:

$$x_1 = 1''$$
$$A = .5'' \times 1'' = .5 in^2$$
$$x_2 = 1.5''$$

$$R_1 = \frac{1}{.00075(1.8)} = 740.7 \frac{^oC}{watt} \quad \text{(Between IC's and Node 121)}$$

$$R_2 = \frac{1.5}{.00075(.18)} = 11{,}111 \frac{^oC}{watt} \quad \text{(Between IC's and Node 127)}$$

3. Timing/Sequencer (T/S) Board

The T/S board contains IC Nodes 41-51 that make their thermal connection to Node 113. Because of manufacturing difficulties, a heat sink was not installed on the T/S board. Because of this, the board is cooled by natural convection. The air node is taken as the case Node 113 since the internal air temperature is assumed to be the same as the case temperature.

The heat transfer coefficient for each IC would be determined by their size since it is vertical. If we use a worst case temperature difference of 50^oC between component and the inner air ambient, the h_c value is approximately $.0042 \frac{watt}{in^2 {}^oC}$.

The thermal resistance between Nodes 47, 48 and Nodes 113 is:

$$A = 0.5'' \times 1.2'' = .6 in^2$$

$$R = \frac{1}{.0042(.6)} = 396.8 \frac{^oC}{watt}$$

The thermal resistance between Nodes 41-46, 49-51 and Node 113 is:

$$A = .75" \times .25" = .19\text{in}^2$$

$$R = \frac{1}{.0042(.19)} = 1253.13 \frac{^\circ C}{\text{watt}}$$

4. <u>Transmitter/Receiver (T/R) Board</u>

The T/R board is shown in Fig 13 with node numbers assigned to the different ICs. The Manchester chip (Node 31) and the clock chip (Node 38) are taller than the other ICs on the board and are in direct contact with the aluminum plate (Node 223) that holds the center and right bulkheads in place, as shown in Fig 14.

The thermal resistance between Node 31 and Node 223 is:

$$R = \frac{x}{KA}$$

$$x = .02\text{in}$$

$$K = .00075 \frac{\text{watts}}{\text{in}^\circ C}$$

$$A = 0.5 \times 1.22 = .61\text{in}^2$$

$$R = \frac{.02}{(.00075)(.61)} = 43.72 \frac{^\circ C}{\text{watt}}$$

The thermal resistance between Node 38 and Node 223 is:

$$R = \frac{x}{KA}$$

$$x = .02\text{in}$$

$$K = .00075 \frac{\text{watts}}{\text{in}^{\circ}\text{C}}$$

$$A = .75 \times .5 = .38\text{in}^2$$

$$R = \frac{.02}{(.00075)(.38)} = 70.18 \frac{^{\circ}\text{C}}{\text{watt}}$$

The remaining IC's on the T/R board dissipate their heat into a copper heat sink (Node 323) as shown in Fig 14. The thermal resistance between the remaining ICs (Nodes 21-30 and Nodes 32-37) and the heat sink is:

$$R = \frac{x}{KA}$$

$$x = .02\text{in}$$

$$K = .00075 \frac{\text{watts}}{\text{in}^{\circ}\text{C}}$$

$$A = .25 \times .75 = .19\text{in}^2$$

$$R = \frac{.02}{(.00075)(.19)} = 140.35 \frac{^{\circ}\text{C}}{\text{watt}}$$

From the copper heat sink (Node 323), the heat is conducted through two aluminum stand-offs (Nodes 423 and 424) to Node 123 as shown in Fig 14. The thermal contact resistance between Nodes 323 and 423 or 424 is:

$$R = \frac{1}{h_c A}$$

$$\frac{1}{h_c} = .3 \text{in}^2 \frac{^{\circ}\text{C}}{\text{watt}}$$

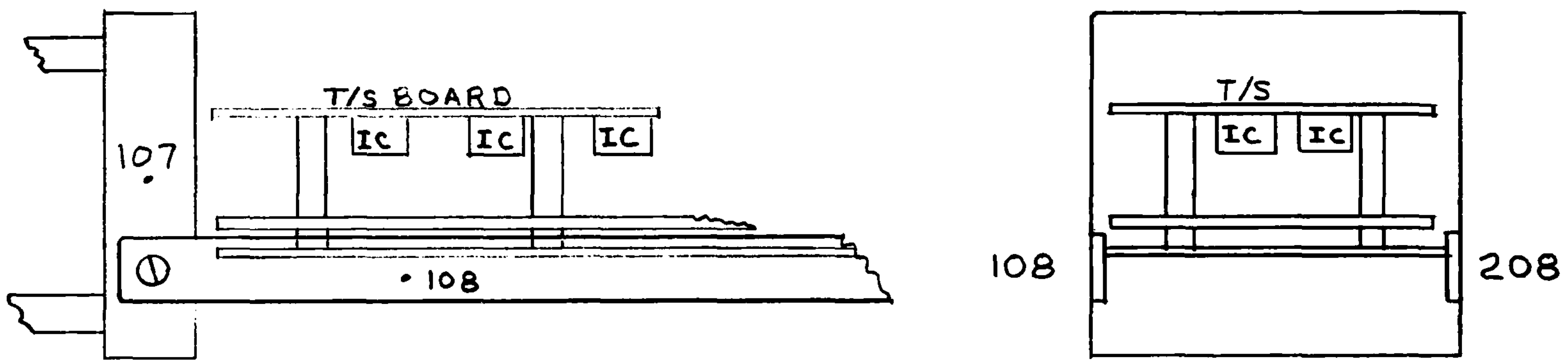


FIGURE 11

T/S BOARD LOCATION

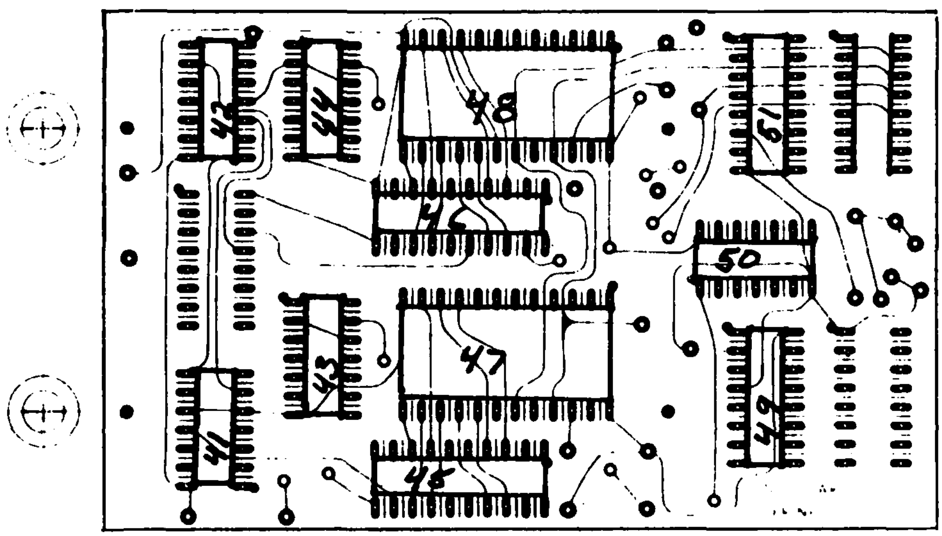


FIGURE 12

T/S BOARD

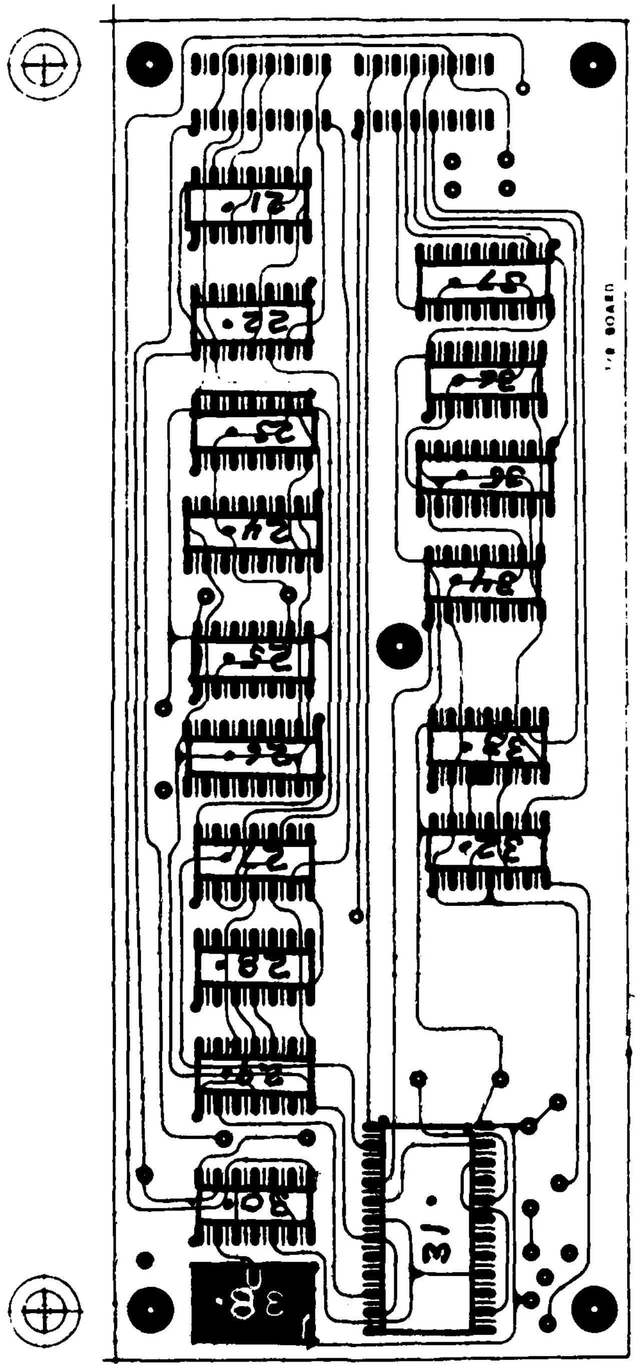


FIGURE 13
T/R BOARD

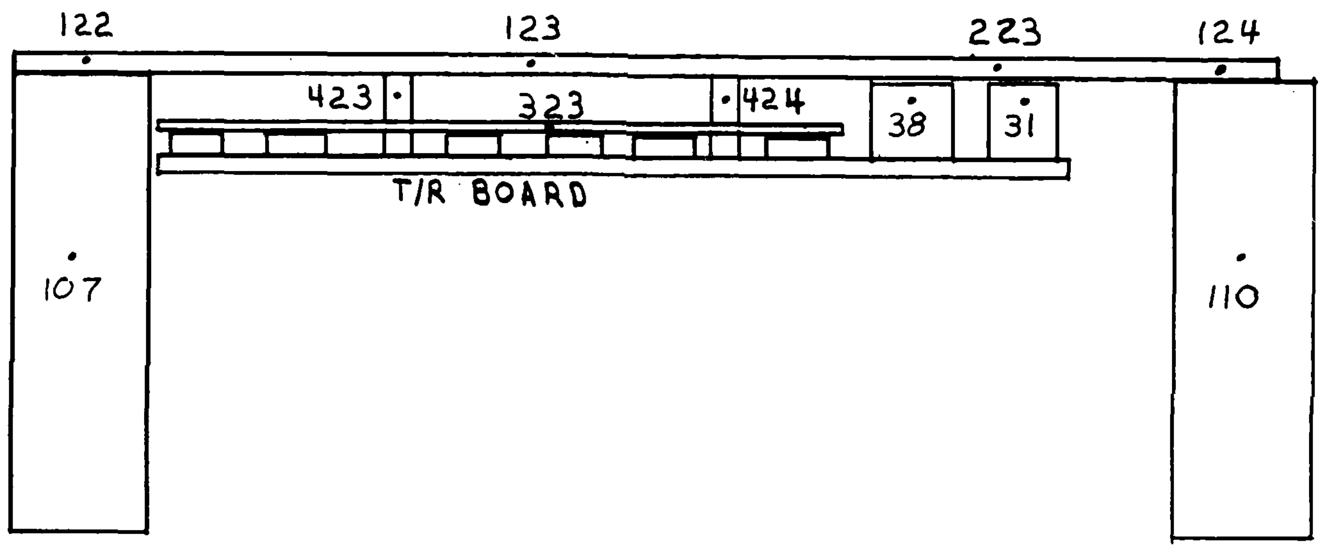


FIGURE 14

T/R BOARD HEAT SINK

$$A = \pi \left(\frac{1}{8}\right)^2 = .05 in^2$$

$$R = \frac{.3}{.05} = 6.11 \frac{^oC}{watt}$$

The thermal resistance between Nodes 423, 424 and the upper support plate (Node 123) (See Fig 8) is the same as calculated above due to symmetry.

5. Power Supply

The large power supply (Node 7) is in contact with each of the two side plates as shown in Fig 6. The thermal resistance between either one of these plates (Nodes 108 or 208) and the large power supply (Node 7) is:

$$R = \frac{x}{KA}$$

$$x = .02 in$$

$$K = .004 \frac{watts}{in^oC}$$ (Ref 1) (This is for a plastic coating on the supply case)

$$A = .65 \times 4.56 = 2.96 in^2$$

$$R = \frac{.02}{(.004)(2.96)} = 1.69 \frac{^oC}{watt}$$

The bottom of the large power supply is in direct contact with the outside case (Node 131) as shown in Fig 7. The thermal resistance between Nodes 7 and 131 is:

$$R = \frac{x}{KA}$$

$$x = .01$$

$$K = .004$$

$$A = 4.56 \times 2.5 = 11.4 in^2$$

$$R = \frac{.01}{(.004)(11.4)} = \frac{.22^oC}{watt}$$

The small power supply is located next to the large power supply (Fig 6) and dissipates its heat into the outside case (Node 134) and also into the two side plates (Nodes 109 and 209). The thermal resistance between Nodes 6 and Nodes 109/209 is:

$$R = \frac{x}{KA}$$

$$x = .02in$$

$$K = .004 \frac{watts}{in^oC}$$

$$A = (.1)(2) = .2in^2$$

$$R = \frac{.02}{(.004)(.2)} = 25.0 \frac{^oC}{watt}$$

The thermal resistance between Nodes 6 and 134 is:

$$R = \frac{x}{KA}$$

$$x = .01 \text{ in}$$

$$K = .004 \frac{watts}{in^oC}$$

$$A = 2 \times 2 = 4\text{in}^2$$

$$R = \frac{.01}{(.004)(4)} = .63\frac{^\circ C}{\text{watt}}$$

The small IC power supply (Node 135) is attached to a heat sink that transfers the heat to the case (Fig 15).

The thermal resistance between Nodes 135 and 235 is:

$$R = \frac{x}{KA}$$

$$x = .02 \text{ in}$$

$$A = 1.25 \times 0.5 = .625\text{in}^2$$

$$K = .004\frac{\text{watts}}{\text{in}^\circ C}$$

$$R = \frac{.02}{(.004)(.625)} = 8.0\frac{^\circ C}{\text{watt}}$$

The thermal resistance between Nodes 235 and 335 (Fig 15) is:

$$R = \frac{x}{KA}$$

$$x = 1\tfrac{1}{4}$$

$$A = \frac{1}{32} \times 1.25 = .04\text{in}^2$$

$$K = 3.5\frac{\text{watts}}{\text{in}^\circ C}$$

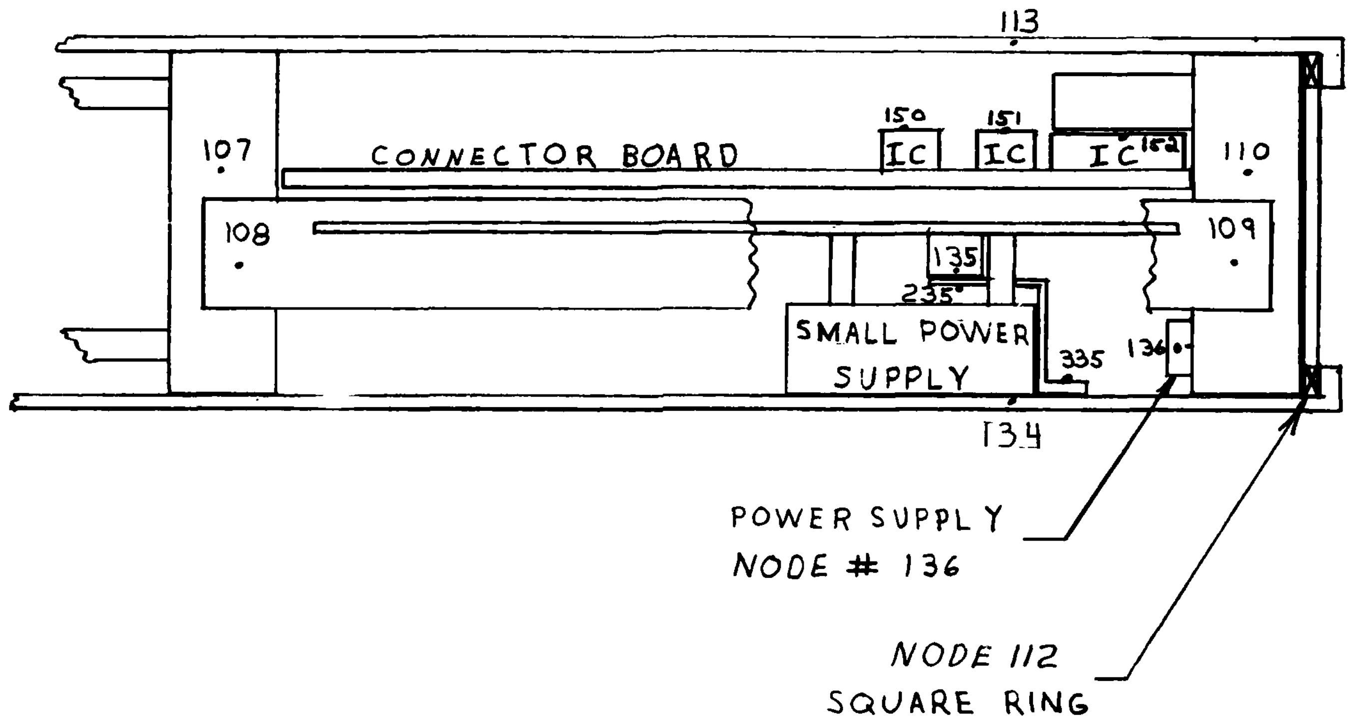


FIGURE 15
POWER SUPPLY LOCATIONS

$$R = \frac{1.25}{(3.5)(.04)} = 8.9 \frac{^{o}C}{watt}$$

The thermal contact resistance between Nodes 335 and 134 (Fig 15) is:

$$R = \frac{1}{h_c A}$$

$$\frac{1}{h_c} = .15 \frac{in^{2\,o}C}{watt}$$

$$R = \frac{.15}{0.3} = 0.5 \frac{^{o}C}{watt}$$

6. <u>Connector Board</u>

There are three ICs mounted on the right side of the connector board as shown in Fig 15. The three ICs have Node numbers 150, 151, and 152 and are shown in Fig 16. Because of manufacturing difficulties, no heat sink could be manufactured for those IC's and they will conduct their heat through the air. The thermal resistance between Nodes 150, 151, 152 and the right bulkhead (Node 110) is:

$$R = \frac{x}{KA}$$

$$x = 0.5 \text{ in}$$

$$K = .00075 \frac{watt}{in\,^{o}C}$$

$$A = 1.2 \times .55 = .66 \text{ in}^2$$

$$R = \frac{0.5}{(.00075)(.66)} = 1010.1 \frac{^{o}C}{watt}$$

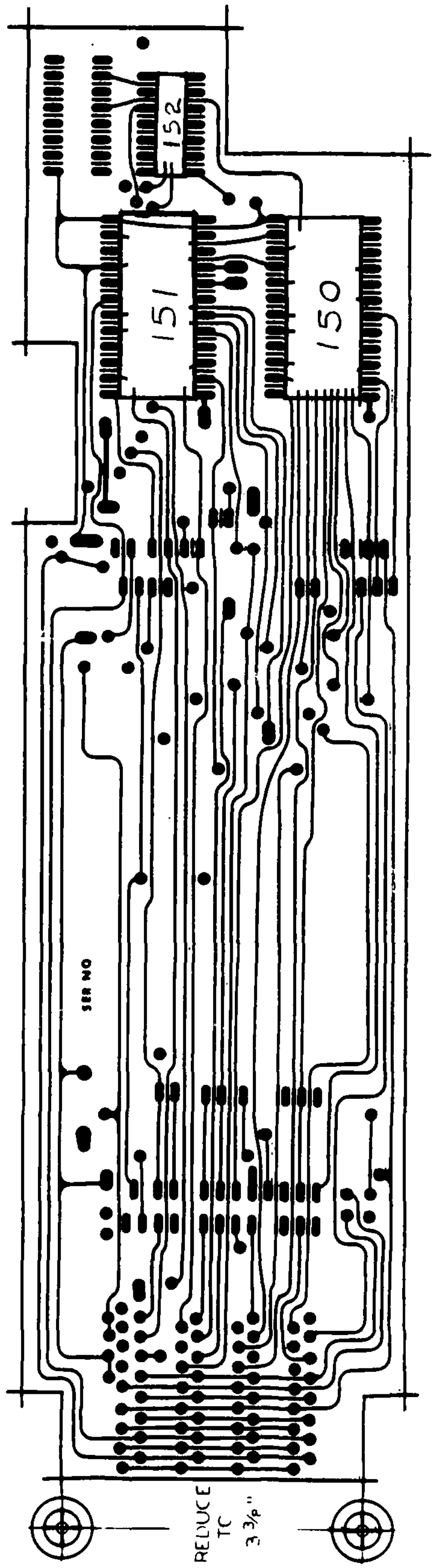


FIGURE 16

CONNECTOR BOARD

There is a small power supply (Node 136) mounted on the right bulkhead (Node 110) as shown in Fig 15. The thermal contact resistance between Nodes 136 and 110 is:

$$R = \frac{1}{\bar{h}_c A}$$

$$\frac{1}{\bar{h}_c} = 0.3 \frac{in^2 C}{watt}$$

$$A = \pi (.5)^2 = .8 in^2$$

$$R = \frac{0.3}{0.8} = \frac{.38^oC}{watt}$$

7. PCM Heat Sink To Chassis

The heat flows from the PCM board heat sinks into the framing studs which have Node numbers 128 and 130 as shown in Fig 4. Two types of thermal resistances exist between Nodes 121 (heat sink) and 128 (stud). There is a conductive resistance between Node 121 and the base of the heat sink, and a contact resistance between the base of the heat sink and the stud. A side view of the heat sink is shown in Fig 5. The cross-hatched portion is the contact area between the heat sink and the stud. Since the two resistances are in series they may be added together to give the total resistance between Nodes 121 and 128 (Fig 4).

For the conductive resistance: $R = \frac{x}{KA}$

Between Nodes 128 - 121
130 - 127

$$x = 1 \text{ in}$$

$$K = 3.5 \frac{watts}{in^oC}$$

$$A = \frac{1}{32} \times 2.75 = .086 in^2$$

(This is for the smallest possible conducting area, which occurs at the bottom of the heat sink)

$$R = \frac{1}{(3.5)(.086)} = 3.32 \frac{^oC}{watt}$$

For the contact resistance: $R = \frac{1}{h_c A}$

$$\frac{1}{h_c} = 0.3 \frac{in^2 \ ^oC}{watt}$$

(Ref 1d)

$$A = 2.75 \times \tfrac{1}{4} = .698 in^2$$

$$R = \frac{0.3}{.688} = .44 \frac{^oC}{watt}$$

$$R_{tot} = R_1 + R_2$$

$$R_{tot} = 3.32 + .44 = 3.76 \frac{^oC}{watt}$$

Because of symmetry, the resistance between Nodes 127 and 130 (Fig 4) is the same as calculated above.

8. PCM Heat Sink

Three nodes are placed on the PCM heat sink as shown in Fig 4. The heat sink is constructed of copper. Between each node there is a conductive heat flow.

Between Nodes 121 - 125 - 127

$$R = \frac{x}{KA}$$

$$x = 2.0 \text{ in}$$

$$K = 3.5 \frac{\text{watts}}{\text{in}^{o}\text{C}} \qquad \text{Ref 1}$$

$$A = \frac{1}{32} \times 4.625" = .145\text{in}^2$$

$$R = \frac{2}{3.5(.145)} = 3.95 \frac{^{o}\text{C}}{\text{watt}}$$

9. <u>Inner Chassis</u>

The inner chassis structure becomes quite complicated but by following Figure 2, we can keep the assumed heat flow paths straight. To make life easy, we will work from the top - down.

Between Nodes 117 and 120, 126, 128, 130

107 and 120, 126, 128, 130

Since each of the connections concerns identical shapes, distances and types of connections, a common thermal resistance value is defined for each. The thermal path consists of both a contact resistance and a conductive one in series. In that case, the two resistances are just additive and

$$R_{total} = R_{contact} + R_{conductive}$$

Contact Resistance: $R_{contact} = \dfrac{1}{h_c A}$

$$\frac{1}{h_c A} = 0.2 \frac{\text{in}^{2\,o}\text{C}}{\text{watt}}$$

(Ref 1) this value is for an aluminum connection and assumed contact pressure of 100psi

A = cross section area of framing stud = .25" x .25" = $.0625 in^2$

$$R = \frac{0.2}{(.0625)} = 3.2 \frac{^oC}{watt}$$

Conduction Resistance: $R = \frac{x}{KA}$

x = distance from bulkhead to mid frame stud = 3.7in

$K = 4.4 \frac{watts}{in^oC}$ (Ref 1a)

A = frame stud cross section area = .25" x .25" = $.0625 in^2$

$$R = \frac{3.7}{4.4(.0625)} = 13.45 \frac{^oC}{watt}$$

The total thermal resistance is therefore

$$R_{tot} = 3.2 + 13.45 = 16.65 \frac{^oC}{watt}$$

Between Nodes 107 and 208, 209
110 and 109, 108

The thermal resistance of the paths between these nodes are the same because of identical shapes, materials and connections. This is a contact resistance between the aluminum struts and the aluminum bulkhead. Machine screws are used as fasteners.

$$\frac{1}{h_c} = 0.3 \ \frac{in^2{}^oC}{watt}$$

this is figured as an average figure because of the large contact area

$A = 0.5" \times 1" = .5in^2$

$$R = \frac{1}{h_c A} = \frac{0.3}{0.5} = .6 \frac{^oC}{watt}$$

Between Nodes 107 and 122
110 and 124

These are contact resistances between aluminum materials fastened by machine screws. Here the contact area is large so again the contact resistances are low.

$$\frac{1}{\bar{h}_c} = 0.3 \frac{in^2 \, {}^oC}{watt}$$

$$A = 0.5''(2.75'') = 1.38in^2$$

$$R = \frac{.3}{1.38} = \frac{.22^oC}{watt}$$

Now each end of each of the longitudinal stringers or plates is, of course, connected to its other end. This thermal resistance is a conductive one and is dependent on the material, shape and distance between nodes.

Between Nodes 208 and 209
108 and 109

$$x = \text{stringer length} = 8.562in$$

$$K = \text{thermal conductivity for aluminum 6061} = \frac{4.4watts}{in^oC}$$

$$A = 1'' \times .0625'' = .0625in^2$$

$$R = \frac{8.562}{4.4(.0625)} = 31.2\frac{^oC}{watt}$$

The thermal resistances between the nodes on the aluminum support plate between bulkheads (Fig 8) are:

Between Nodes 123 and 223 $\quad R = \frac{x}{KA}$

$$x = 3.75 \text{ in}$$

$$K = \frac{4.4\text{watts}}{\text{in}^{o}\text{C}}$$

$$A = 2.75\frac{(1)}{8} = .34\text{in}^2$$

$$R = \frac{3.75}{4.4(.34)} = 2.48$$

Between Nodes 122 and 123 $\quad x = 3.25$ in

$$K = \frac{4.4\text{watts}}{\text{in}^{o}\text{C}}$$

$$A = .34\text{in}^2$$

$$R = \frac{3.25}{(4.4)(.34)} = 2.48 \frac{^{o}\text{C}}{\text{watt}}$$

Between Nodes 223 and 124 $\quad x = 2.6$in

$$K = \frac{4.4\text{watts}}{\text{in}^{o}\text{C}}$$

$$A = .34\text{in}^2$$

$$R = \frac{2.6}{4.4(.34)} = 1.69$$

The thermal resistance between Node 110 (right bulkhead) and Node 112 (square ring) is:

$$R = \frac{1}{h_c A}$$

$$\frac{1}{h_c} = 0.3\frac{in^2\,{}^oC}{watt}$$

$$A = 2in^2$$

$$R = \frac{0.3}{2} = .15\frac{{}^oC}{watt}$$

10. <u>Case Exterior</u>

The heat flows from the left bulkhead to the outside case and is then dissipated into the surrounding air. The thermal resistance between the left bulkhead (Node 117) and the outside case (Nodes 116/133) is calculated as follows:

There is a contact resistance between the bulkhead and the case and a conductive resistance between the end of the case and Node 116.

For the contact resistance: $R = \frac{1}{h_c A}$

$$\frac{1}{h_c} = .3\frac{in^2\ {}^oC}{watt}$$

The total contact area between the left bulkhead and the case is:

A = (length of one side) (4 sides)(contact width)

$A = (3.0)(4)(.35) = 4.2in^2$

The contact area for the top half of the case (Node 116) is:

$A = 4.2/2 = 2.1in^2$

$$R_{(contact)} = \frac{0.3}{2.1} = .14\frac{{}^oC}{watt}$$

The conductive resistance between the end of the case and Node 116 is:

$$R = \frac{x}{KA}$$

$$x = 3.6\text{in}$$

$$K = 4.4 \frac{\text{watts}}{\text{in}^{o}\text{C}}$$

$$A = 3.0\ (2)(1/16) = .375$$

$$R_{conduct} = \frac{3.6}{4.4(.375)} = 2.18 \frac{^{o}\text{C}}{\text{watt}}$$

The total thermal resistance between the left bulkhead (Node 117) and the first Node on the top of the case (Node 116) is the sum of the contact resistance and the conductive resistance

$$R = .14 + 2.18 = 2.32 \frac{^{o}\text{C}}{\text{watt}}$$

Because of symmetry, the thermal resistance between Node 117 and Node 133 (Fig 7) is the same as calculated above.

Figure 2 shows the connections between the following case nodes:

116 and 115
115 and 114
114 and 113
133 and 132
132 and 131
131 and 134

The thermal resistance between each pair of nodes is:

$$R = \frac{x}{KA}$$

$$x = 3.6\text{in}$$

$$K = 4.4 \frac{\text{watts}}{\text{in}^{\text{o}}\text{C}}$$

$$A = .375\text{in}^2$$

$$R = \frac{3.6}{4.4(.375)} = 2.18 \frac{^{\text{o}}\text{C}}{\text{watt}}$$

Figure 2 shows the connections between the following pairs of nodes:

116 and 133

115 and 132

114 and 131

113 and 134

The thermal resistance between them is:

$$R = \frac{x}{KA}$$

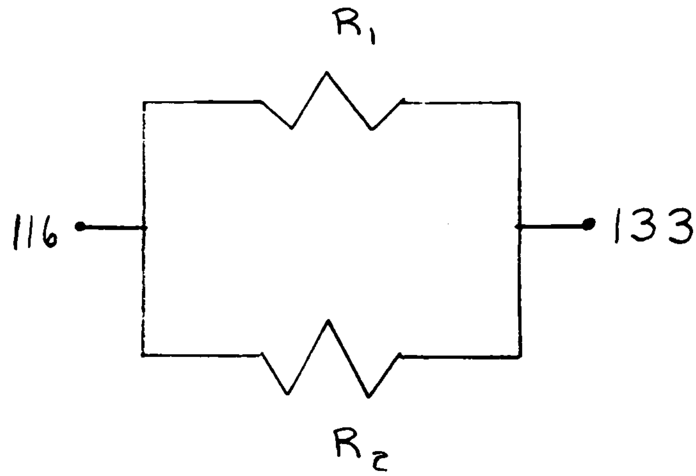
$x = 6\text{in}$ (this is the perimeter from the top to the bottom of the case)

$$K = 4.4 \frac{\text{watts}}{\text{in}^{\text{o}}\text{C}}$$

$$A = 1/16(3.6) = .23$$

$$R = \frac{6}{4.4(.23)} = 6.06 \frac{^{\text{o}}\text{C}}{\text{watt}}$$

The thermal circuit between Nodes 116 and 133 is shown below:



Since these two resistances are in parallel, the equivalent thermal resistance between Nodes 116 and 133 is calculated as follows:

$$\frac{1}{Req} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots..$$

$$\frac{1}{Req} = \frac{1}{6.06} + \frac{1}{6.06}$$

$$Req = 3.03 \frac{{}^{o}C}{\text{watt}}$$

The heat is transferred by convection from the case nodes (113-116, 131-134) to the ambient air (Node 1). First the natural convection coefficient (h_c) is calculated using Equation 2 and then Equation 3 is used to calculate the thermal resistance between the case and the air

$$h_c = 1.062 \times 10^{-3} \left(\frac{T}{L}\right)^{0.25}$$

$$T = 10^oC$$

$$L = 2ft$$

$$h_c = 1.062 \times 10^{-3} \left(\frac{10}{2}\right)^{0.25}$$

$$h_c = .002 \frac{watt}{^oC\ in^2}$$

$$R = \frac{1}{h_c A}$$

$$A = 6 \times 3.6 = 21.6in^2$$

$$R = \frac{1}{(21.6)(.002)} = 23.15 \frac{^oC}{watt}$$

VI COMPUTER INPUT AND RESULTS

The following pages contain the input data for the computer analysis and the results of the analysis. Table 1 shows the heat output of each node. Table 2 shows the thermal resistances between nodes and the assigned connector numbers for these resistances. Table 3 is the actual computer input, and Table 4 contains the results where temperature is given in ^oF for each node.

TABLE 1

SOURCE DATA SUMMARY

NODE	IC	IC HEAT OUTPUT WATTS	BTU/HR
PCM			
60	S3505	.5	1.707
61	S3505	.5	1.707
63	S3505	.5	1.707
64	54LS500	.044	.150216
65	54LS08	.044	.150216
66	54LS00	.033	.112662
67	54LS04	.044	.150216
70	S3505	.5	1.707
71	S3505	.5	1.707
72	S3505	.5	1.707
73	S3505	.5	1.707
74	54LS500	.044	.150216
75	54LS08	.044	.150216
76	54LS00	.033	.112662
77	54LS04	.044	.150216
80	S3505	.5	1.707
81	S3505	.5	1.707
82	S3505	.5	1.707
83	S3505	.5	1.707
84	54LS500	.044	.150216
85	54LS08	.044	.150216
86	54LS00	.033	.112662
87	54LS04	.044	.150216

TABLE 1 (Con't)

NODE	IC	IC HEAT OUTPUT WATTS	BTU/HR
PUSH TO TALK			
290	54LS86	.055	.18777
291	54LS86	.055	.18777
292	54LS04	.037	.126318
DIGITAL			
91	S3505	.5	1.707
92	54LS04	.033	.112662
93	54LS08	.033	.10242
94	54LS00	.044	.150216
95	54LS75	.04	.13656
96	54LS165	.18	.61452
97	54LS165	.18	.61452
98	54LS273	.14	.47796
99	54LS273	.14	.47796
100	54LS164	.135	.46089
101	54LS00	.180	.61452
102	54LS04	.033	.112662
T/S			
41	54LS271	.033	.112662
42	54LS04	.033	.112662
43	54LS393	.150	.5121
44	54LS393	.15	.5121
45	54LS273	.14	.47796
46	27L08	.14	.47796
47	54LS273	.416	1.420224
48	27L08	.416	1.420224
49	54LS138	.05	.1707
50	54LS393	.15	.5121
51	54LS138	.05	.1707

TABLE 1 (Con't)

NODE	IC	IC HEAT OUTPUT WATTS	BTU/HR
T/R			
21	5425	.095	.32433
22	54LS04	.033	.112662
23	54LS164	.135	.46089
24	54LS165	.180	.61452
25	54LS164	.135	.46089
26	54LS165	.180	.61452
27	54LS08	.044	.150216
28	54LS74	.04	.13656
29	54LS74	.04	.13656
30	54LS00	.044	.150216
31	HD15530	.05	.1707
32	54LS74	.04	.13656
33	54LS08	.044	.150216
34	54LS164	.135	.46089
35	54LS165	.180	.61452
36	54LS164	.135	.46089
37	54LS165	.180	.61452
38	clock chip	.1	.3414
POWER SUPPLY			
7	LG PS	8.0	27.312
8	SM PS	2.0	6.828
135		1.9	6.4866
CONN BOARD			
150	7804	1.0	3.414
151	7804	1.0	3.414
152	54LS04	.033	.112662
136	LM117	6.0	20.484

TABLE 2

THERMAL RESISTANCES SUMMARY

CONN NO.	IC NODE	HEAT SINK NODE	THERMAL RESISTANCE $^{o}C/WATT$	THERMAL CONDUCTANCE WATTS/^{o}C	BTU/HR^{o}F
PCM					
1	60	121	48.49	2.06×10^{-2}	3.91×10^{-2}
2	61	121	48.49	2.06×10^{-2}	3.91×10^{-2}
3	62	121	48.49	2.06×10^{-2}	3.91×10^{-2}
4	63	121	49.49	2.06×20^{-2}	3.91×10^{-2}
5	64	121	1108.2	9.02×10^{-4}	1.71×10^{-3}
6	65	121	1108.2	9.02×10^{-4}	1.71×10^{-3}
7	66	121	1108.2	9.02×10^{-4}	1.71×10^{-3}
8	67	121	1108.2	9.02×10^{-4}	1.71×10^{-3}
9	70	125	48.49	2.06×10^{-2}	3.91×10^{-2}
10	71	125	48.49	2.06×10^{-2}	3.91×10^{-2}
11	72	125	48.49	2.06×10^{-2}	3.91×10^{-2}
12	73	125	48.49	2.06×10^{-2}	3.91×10^{-2}
13	74	125	1108.2	9.02×10^{-4}	1.71×10^{-3}
14	75	125	1108.2	9.02×10^{-4}	1.71×10^{-3}
15	76	125	1108.2	9.02×10^{-4}	1.71×10^{-3}
16	77	125	1108.2	9.02×10^{-4}	1.71×10^{-3}
17	80	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
18	81	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
19	82	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
20	83	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
21	84	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
22	85	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
23	86	127	1108.2	9.02×10^{-4}	1.71×10^{-3}
24	87	127	1108.2	9.02×10^{-4}	1.71×10^{-3}

TABLE 2 (Con't)

CONN NO.	IC NODE	HEAT SINK NODE	THERMAL RESISTANCE ^{o}C/WATT	THERMAL CONDUCTANCE WATTS/^{o}C	BTU/HR^{o}F
PCM PUSH TO TALK					
25	290	125	1852.	5.4×10^{-4}	1.02×10^{-3}
26	291	125	1852.	5.4×10^{-4}	1.02×10^{-3}
27	292	125	1852.	5.4×10^{-4}	1.02×10^{-3}
PCM DIGITAL					
28	91	121	740.7	1.35×10^{-3}	2.56×10^{-3}
29	92	121	740.7	1.35×10^{-3}	2.56×10^{-3}
30	93	121	740.7	1.35×10^{-3}	2.56×10^{-3}
31	94	121	740.7	1.35×10^{-3}	2.56×10^{-3}
32	95	121	740.7	1.35×10^{-3}	2.56×10^{-3}
33	96	121	740.7	1.35×10^{-3}	2.56×10^{-3}
34	97	121	740.7	1.35×10^{-3}	2.56×10^{-3}
35	98	121	740.7	1.35×10^{-3}	2.56×10^{-3}
36	99	121	740.7	1.35×10^{-3}	2.56×10^{-3}
37	100	121	740.7	1.35×10^{-3}	2.56×10^{-3}
38	101	121	740.7	1.35×10^{-3}	2.56×10^{-3}
39	102	121	740.7	1.35×10^{-3}	2.56×10^{-3}
40	91	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
41	92	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
42	93	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
43	94	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
44	95	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
45	96	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
46	97	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
47	98	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
48	99	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
49	100	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
50	101	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}
51	102	127	11,111	$9. \times 10^{-5}$	1.71×10^{-4}

TABLE 2 (Con't)

CONN NO.	IC NODE	HEAT SINK NODE	THERMAL RESISTANCE ^{o}C/WATT	THERMAL CONDUCTANCE WATTS/^{o}C	BTU/HR^{o}F
T/S					
52	41	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
53	42	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
54	43	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
55	44	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
56	45	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
57	46	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
58	47	113	396.8	2.52×10^{-3}	4.78×10^{-3}
59	48	113	396.8	2.52×10^{-3}	4.78×10^{-3}
60	49	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
61	50	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
62	51	113	1253.13	7.98×10^{-4}	1.51×10^{-3}
T/R					
63	21	323	140.35	7.13×10^{-3}	1.35×10^{-2}
64	22	323	140.35	7.13×10^{-3}	1.35×10^{-2}
65	23	323	140.35	7.13×10^{-3}	1.35×10^{-2}
66	24	323	140.35	7.13×10^{-3}	1.35×10^{-2}
67	25	323	140.35	7.13×10^{-3}	1.35×10^{-2}
68	26	323	140.35	7.13×10^{-3}	1.35×10^{-2}
69	27	323	140.35	7.13×10^{-3}	1.35×10^{-2}
70	28	323	140.35	7.13×10^{-3}	1.35×10^{-2}
71	29	323	140.35	7.13×10^{-3}	1.35×10^{-2}
72	30	323	140.35	7.13×10^{-3}	1.35×10^{-2}
73	31	223	43.72	2.29×10^{-2}	4.34×10^{-2}
74	32	323	140.35	7.13×10^{-3}	1.35×10^{-2}
75	33	323	140.35	7.13×10^{-3}	1.35×10^{-2}
76	34	343	140.35	7.13×10^{-3}	1.35×10^{-2}
77	35	323	140.35	7.13×10^{-3}	1.35×10^{-2}
78	36	323	140.35	7.13×10^{-3}	1.35×10^{-2}
79	37	323	140.35	7.13×10^{-3}	1.35×10^{-2}
80	38	223	70.18	1.43×10^{-2}	2.7×10^{-2}

TABLE 2 (Con't)

CONN NO.	IC NODE	HEAT SINK NODE	THERMAL RESISTANCE °C/WATT	THERMAL CONDUCTANCE WATTS/°C	BTU/HR°F
81	323	423	6.11	1.64×10^{-1}	3.1×10^{-1}
82	323	424	6.11	1.64×10^{-1}	3.1×10^{-1}
83	423	123	6.11	1.64×10^{-1}	3.1×10^{-1}
84	424	123	6.11	1.64×10^{-1}	3.1×10^{-1}
POWER SUPPLY					
85	7	108	1.69	5.92×10^{-1}	1.12
86	7	208	1.69	5.92×10^{-1}	1.12
87	7	131	.22	4.55	8.62
88	6	109	25.	.04	7.58×10^{-2}
89	6	209	25.	.04	7.58×10^{-2}
90	6	134	.63	1.59	3.01
91	135	235	8.0	.125	2.37×10^{-1}
92	235	335	8.9	1.12×10^{-1}	2.13×10^{-1}
93	335	134	.5	2.	3.79
CONNECTOR BOARD					
94	150	110	1010.1	9.9×10^{-4}	1.88×10^{-3}
95	151	110	1010.1	9.9×10^{-4}	1.88×10^{-3}
96	152	110	1010.1	9.9×10^{-4}	1.88×10^{-3}
97	136	110	.38	2.63	4.98
PCM HEAT SINK					
98	121	125	3.95	2.53×10^{-1}	.48
99	125	127	3.95	2.53×10^{-1}	.48
PCM HEAT SINK TO CHASSIS					
100	121	128	3.76	2.66×10^{-1}	.50
101	127	130	3.76	2.66×10^{-1}	.50

TABLE 2 (Con't)

CONN NO.	IC NODE	HEAT SINK NODE	THERMAL RESISTANCE ^{o}C/WATT	THERMAL CONDUCTANCE WATTS/^{o}C	BTU/HR^{o}F
INNER CHASSIS					
102	117	120	16.65	6.0×10^{-2}	1.14×10^{-1}
103	117	126	16.65	6.0×10^{-2}	1.14×10^{-1}
104	117	128	16.65	6.0×10^{-2}	1.14×10^{-1}
105	117	130	16.65	6.0×10^{-2}	1.14×10^{-1}
106	117	120	16.65	6.0×10^{-2}	1.14×10^{-1}
107	117	126	16.65	6.0×10^{-2}	1.14×10^{-1}
108	117	128	16.65	6.0×10^{-2}	1.14×10^{-1}
109	107	130	16.65	6.0×10^{-2}	1.14×10^{-1}
110	107	208	.6	1.67	3.16
111	107	209	.6	1.67	3.16
112	110	109	.6	1.67	3.16
113	110	108	.6	1.67	3.16
114	107	122	.22	4.55	8.62
115	110	124	.22	4.55	8.62
116	208	209	31.2	3.21×10^{-2}	6.08×10^{-2}
117	108	109	31.2	3.21×10^{-2}	6.08×10^{-2}
118	123	223	2.48	.40	.77
119	122	123	2.48	.40	.77
120	223	124	1.69	5.92×10^{-1}	1.12
121	110	112	.15	6.67	12.64
CASE EXTERIOR					
122	117	116	2.31	.433	.82
123	117	133	2.31	.433	.82

TABLE 2 (Con't)

CONN NO.	IC NODE	HEAT SINK NODE	THERMAL RESISTANCE ^oC/WATT	THERMAL CONDUCTANCE WATTS/^oC	BTU/HR^oF
124	116	115	2.18	.46	.87
125	115	114	2.18	.46	.87
126	114	113	2.18	.46	.87
127	133	132	2.18	.46	.87
128	132	131	2.18	.46	.87
129	131	134	2.18	.46	.87
130	116	133	3.03	.33	.626
131	115	132	3.03	.33	.626
132	114	131	3.03	.33	.626
133	113	134	3.03	.33	.626
134	113	1	23.15	.043	.082
135	114	1	23.15	.043	.082
136	115	1	23.15	.043	.082
137	116	1	23.15	.043	.082
138	131	1	23.15	.043	.082
139	132	1	23.15	.043	.082
140	133	1	23.15	.043	.082
141	134	1	23.15	.043	.082

TABLE 3

COMPUTER INPUT

```
RAS, T100, I070, CM230000.   D800685, RADC, 53021.
ATTACH, SINDA, SINDABNRY, ID=D800016, SN=AFFDL, MR=1.
ATTACH, LIB, SINDLIB, ID=D800016, SN=AFFDL, MR=1.
LIBRARY, LIB.
SINDA.
RETURN, SINDA.
REWIND, TAPE12, TAPE13, TAPE4.
FTN, I=TAPE13, B=SNDALGO, R.
SNDALGO.
RETURN, SNDALGO, LIB, TAPE4, TAPE13, TAPE12.
*EOR

          BCD 3THERMAL SPCS
          BCD 3ASOC REMOTING
          END
          BCD 3NODE DATA
               60, 125. 0, -1. 0
               61, 125. 0, -1. 0
               62, 125. 0, -1. 0
               63, 125. 0, -1. 0
               64, 125. 0, -1. 0
               65, 125. 0, -1. 0
               66, 125. 0, -1. 0
               67, 125. 0, -1. 0
               121, 125. 0, -1. 0
               70, 125. 0, -1. 0
               71, 125. 0, -1. 0
               72, 125. 0, -1. 0
               73, 125. 0, -1. 0
               74, 125. 0, -1. 0
               75, 125. 0, -1. 0
               76, 125. 0, -1. 0
               77, 125. 0, -1. 0
               125, 125. 0, -1. 0
               80, 125. 0, -1. 0
               81, 125. 0, -1. 0
               82, 125. 0, -1. 0
               83, 125. 0, -1. 0
               84, 125. 0, -1. 0
               85, 125. 0, -1. 0
               86, 125. 0, -1. 0
               87, 125. 0, -1. 0
               127, 125. 0, -1. 0
               290, 125. 0, -1. 0
               291, 125. 0, -1. 0
               292, 125. 0, -1. 0
               91, 125. 0, -1. 0
               92, 125. 0, -1. 0
               93, 125. 0, -1. 0
               94, 125. 0, -1. 0
               95, 125. 0, -1. 0
               96, 125. 0, -1. 0
               97, 125. 0, -1. 0
               98, 125. 0, -1. 0
               99, 125. 0, -1. 0
               100, 125. 0, -1. 0
               101, 125. 0, -1. 0
               102, 125. 0, -1. 0
```

TABLE 3 (con't)

```
41,125.0,-1.0
42,125.0,-1.0
43,125.0,-1.0
44,125.0,-1.0
45,125.0,-1.0
46,125.0,-1.0
47,125.0,-1.0
48,125.0,-1.0
49,125.0,-1.0
50,125.0,-1.0
51,125.0,-1.0
21,125.0,-1.0
22,125.0,-1.0
23,125.0,-1.0
24,125.0,-1.0
25,125.0,-1.0
26,125.0,-1.0
27,125.0,-1.0
28,125.0,-1.0
29,125.0,-1.0
30,125.0,-1.0
31,125.0,-1.0
32,125.0,-1.0
33,125.0,-1.0
34,125.0,-1.0
35,125.0,-1.0
36,125.0,-1.0
37,125.0,-1.0
38,125.0,-1.0
323,125.0,-1.0
423,125.0,-1.0
424,125.0,-1.0
7,125.0,-1.0
6,125.0,-1.0
135,125.0,-1.0
235,125.0,-1.0
335,125.0,-1.0
150,125.0,-1.0
151,125.0,-1.0
152,125.0,-1.0
136,125.0,-1.0
117,125.0,-1.0
120,125.0,-1.0
126,125.0,-1.0
128,125.0,-1.0
130,125.0,-1.0
107,125.0,-1.0
208,125.0,-1.0
108,125.0,-1.0
122,125.0,-1.0
123,125.0,-1.0
223,125.0,-1.0
209,125.0,-1.0
109,125.0,-1.0
124,125.0,-1.0
110,125.0,-1.0
112,125.0,-1.0
133,125.0,-1.0
116,125.0,-1.0
132,125.0,-1.0
```

Table 3 (con't)

```
        115,125.0,-1.0
        131,125.0,-1.0
        114,125.0,-1.0
        134,125.0,-1.0
        113,125.0,-1.0
        -1,125.0,1.0
END
BCD 3SOURCE DATA
        60,1.707
        61,1.707
        62,1.707
        63,1.707
        64,.150216
        65,.150216
        66,.112662
        67,.150216
        70,1.707
        71,1.707
        72,1.707
        73,1.707
        74,.150216
        75,.150216
        76,.112662
        77,.150216
        80,1.707
        81,1.707
        82,1.707
        83,1.707
        84,.150216
        85,.150216
        86,.112662
        87,.150216
        290,.18777
        291,.18777
        292,.126318
        91,1.707
        92,.112662
        93,.10242
        94,.150216
        95,.13656
        96,.61452
        97,.61452
        98,.47796
        99,.47796
        100,.46089
        101,.61452
        102,.112662
        41,.112662
        42,.112662
        43,.5121
        44,.5121
        45,.47796
        46,.47796
        47,1.420224
        48,1.420224
        49,.1707
        50,.5121
        51,.1707
        21,.32433
        22,.112662
```

TABLE 3 (con't)

```
        23,.46089
        24,.61452
        25,.46089
        26,.61452
        27,.150216
        28,.13656
        29,.13656
        30,.150216
        31,.1707
        32,.13656
        33,.150216
        34,.46089
        35,.61452
        36,.46089
        37,.61452
        38,.3414
        7,27.312
        6,6.828
        135,6.4866
        150,3.414
        151,3.414
        152,.112662
        136,20.484
END
BCD 3CONDUCTOR DATA
        1,60,121,.0391
        2,61,121,.0391
        3,62,121,.0391
        4,63,121,.0391
        5,64,121,.00171
        6,65,121,.00171
        7,66,121,.00171
        8,67,121,.00171
        9,70,125,.0391
        10,71,125,.0391
        11,72,125,.0391
        12,73,125,.0391
        13,74,125,.00171
        14,75,125,.00171
        15,76,125,.00171
        16,77,125,.00171
        17,80,127,.0391
        18,81,127,.0391
        19,82,127,.0391
        20,83,127,.0391
        21,84,127,.00171
        22,85,127,.00171
        23,86,127,.00171
        24,87,127,.00171
        25,290,125,.00102
        26,291,125,.00102
        27,292,125,.00102
        28,91,121,.00256
        29,92,121,.00256
        30,93,121,.00256
        31,94,121,.00256
        32,95,121,.00256
        33,96,121,.00256
        34,97,121,.00256
        35,98,121,.00256
```

TABLE 3 (con't)

36, 99, 121, .00256
37, 100, 121, .00256
38, 101, 121, .00256
39, 102, 121, .00256
40, 91, 127, .000171
41, 92, 127, .000171
42, 93, 127, .000171
43, 94, 127, .000171
44, 95, 127, .000171
45, 96, 127, .000171
46, 97, 127, .000171
47, 98, 127, .000171
48, 99, 127, .000171
49, 100, 127, .000171
50, 101, 127, .000171
51, 102, 127, .000171
52, 41, 113, .00151
53, 42, 113, .00151
54, 43, 113, .00151
55, 44, 113, .00151
56, 45, 113, .00151
57, 46, 113, .00151
58, 47, 113, .00478
59, 48, 113, .00478
60, 49, 113, .00151
61, 50, 113, .00151
62, 51, 113, .00151
63, 21, 323, .0135
64, 22, 323, .0135
65, 23, 323, .0135
66, 24, 323, .0135
67, 25, 323, .0135
68, 26, 323, .0135
69, 27, 323, .0135
70, 28, 323, .0135
71, 29, 323, .0135
72, 30, 323, .0135
73, 31, 223, .0434
74, 32, 323, .0135
75, 33, 323, .0135
76, 34, 323, .0135
77, 35, 323, .0135
78, 36, 323, .0135
79, 37, 323, .0135
80, 38, 223, .027
81, 323, 423, .31
82, 323, 424, .31
83, 423, 123, .31
84, 424, 123, .31
85, 7, 108, 1.12
86, 7, 208, 1.12
87, 7, 131, 8.62
88, 6, 109, .0758
89, 6, 209, .0758
90, 6, 134, 3.01
91, 135, 235, .237
92, 235, 335, .213
93, 335, 134, 3.79
94, 150, 110, .00188
95, 151, 110, .00188

TABLE 3 (con't)

```
            96,152,110,.00188
            97,136,110,4.98
            98,121,125,.48
            99,125,127,.48
            100,121,128,.50
            101,127,130,.50
            102,117,120,.114
            103,117,126,.114
            104,117,128,.114
            105,117,130,.114
            106,107,120,.114
            107,107,126,.114
            108,107,128,.114
            109,107,130,.114
            110,107,208,3.16
            111,107,209,3.16
            112,110,109,3.16
            113,110,108,3.16
            114,107,122,8.62
            115,110,124,8.62
            116,208,209,.0608
            117,108,109,.0608
            118,123,223,.77
            119,122,123,.77
            120,223,124,1.12
            121,110,112,12.64
            122,117,116,.82
            123,117,133,.82
            124,116,115,.87
            125,115,114,.87
            126,114,113,.87
            127,133,132,.87
            128,132,131,.87
            129,131,134,.87
            130,116,133,.626
            131,115,132,.626
            132,114,131,.626
            133,113,134,.626
            134,113,1,.082
            135,114,1,.082
            136,115,1,.082
            137,116,1,.082
            138,131,1,.082
            139,132,1,.082
            140,133,1,.082
            141,134,1,.082
        END
        BCD 3CONSTANTS DATA
            NLOOP=100,ARLXCA=1.0,DRLXCA=1.0
        END
        BCD 3ARRAY DATA
        END
        BCD 3EXECUTION
F       DIMENSION X(125)
F       NDIM=125
F       NTH=0
            CINDSS
        END
        BCD 3VARIABLES 1
        END
```

TABLE 3 (con't)

```
BCD 3VARIABLES 2
END
BCD 3OUTPUT CALLS
    TPRINT
END
BCD 3END OF DATA
```

TABLE 4

INDA RESULTS

```
*EOR
1    SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER    - - - S

     ASOC REMOTING

***********
TIME=      0.00000 DTIMEU= 0.              CSGMIN(      0)= 0.

T      60= 1.25000E+02   T      61= 1.25000E+02   T      62= 1.25000E+02
T      66= 1.25000E+02   T      67= 1.25000E+02   T     121= 1.25000E+02
T      73= 1.25000E+02   T      74= 1.25000E+02   T      75= 1.25000E+02
T      80= 1.25000E+02   T      81= 1.25000E+02   T      82= 1.25000E+02
T      86= 1.25000E+02   T      87= 1.25000E+02   T     127= 1.25000E+02
T      91= 1.25000E+02   T      92= 1.25000E+02   T      93= 1.25000E+02
T      97= 1.25000E+02   T      98= 1.25000E+02   T      99= 1.25000E+02
T      41= 1.25000E+02   T      42= 1.25000E+02   T      43= 1.25000E+02
T      47= 1.25000E+02   T      48= 1.25000E+02   T      49= 1.25000E+02
T      22= 1.25000E+02   T      23= 1.25000E+02   T      24= 1.25000E+02
T      28= 1.25000E+02   T      29= 1.25000E+02   T      30= 1.25000E+02
T      34= 1.25000E+02   T      35= 1.25000E+02   T      36= 1.25000E+02



T     423= 1.25000E+02   T     424= 1.25000E+02   T       7= 1.25000E+02
T     335= 1.25000E+02   T     150= 1.25000E+02   T     151= 1.25000E+02
T     120= 1.25000E+02   T     126= 1.25000E+02   T     128= 1.25000E+02
T     108= 1.25000E+02   T     122= 1.25000E+02   T     123= 1.25000E+02
T     124= 1.25000E+02   T     110= 1.25000E+02   T     112= 1.25000E+02
T     115= 1.25000E+02   T     131= 1.25000E+02   T     114= 1.25000E+02

***********
TIME=      0.00000 DTIMEU= 0.              CSGMIN(      0)= 0.

T      60= 3.11459E+02   T      61= 3.11459E+02   T      62= 3.11459E+02
T      66= 3.33686E+02   T      67= 3.55647E+02   T     121= 2.68700E+02
T      73= 3.15626E+02   T      74= 3.59814E+02   T      75= 3.59814E+02
T      80= 3.04564E+02   T      81= 3.04564E+02   T      82= 3.04564E+02
T      86= 3.26791E+02   T      87= 3.48752E+02   T     127= 2.61797E+02
T      91= 8.93314E+02   T      92= 3.00521E+02   T      93= 3.05771E+02
T      97= 4.93284E+02   T      98= 4.43281E+02   T      99= 4.43281E+02
T      41= 2.53503E+02   T      42= 2.53503E+02   T      43= 5.18032E+02
T      47= 4.76011E+02   T      48= 4.76011E+02   T      49= 2.91939E+02
T      22= 2.08305E+02   T      23= 2.32160E+02   T      24= 2.43540E+02
T      28= 2.08135E+02   T      29= 2.08135E+02   T      30= 2.09147E+02
T      34= 2.32160E+02   T      35= 2.43540E+02   T      36= 2.32160E+02
T     423= 1.91302E+02   T     424= 1.91302E+02   T       7= 1.83590E+02
T     335= 1.83298E+02   T     150= 1.99623E+03   T     151= 1.99623E+03
T     120= 1.82057E+02   T     126= 1.82057E+02   T     128= 2.41565E+02
T     108= 1.81113E+02   T     122= 1.82902E+02   T     123= 1.84561E+02
T     124= 1.80442E+02   T     110= 1.81248E+02   T     112= 1.81248E+02
T     115= 1.73430E+02   T     131= 1.81858E+02   T     114= 1.75904E+02

LOOPCT =      55 ENGBAL =    .73995E+02

     END OF DATA
*EOR
```

TABLE 4 (con't)

SINDA - - - CDC 6600 VERSION PAGE 1

TEMPCC(0)= 0. RELXCC(0)= 0.

T 63=	1.25000E+02	T 64=	1.25000E+02	T 65=	1.25000E+02
T 70=	1.25000E+02	T 71=	1.25000E+02	T 72=	1.25000E+02
T 76=	1.25000E+02	T 77=	1.25000E+02	T 125=	1.25000E+02
T 83=	1.25000E+02	T 84=	1.25000E+02	T 85=	1.25000E+02
T 290=	1.25000E+02	T 291=	1.25000E+02	T 294=	1.25000E+02
T 94=	1.25000E+02	T 95=	1.25000E+02	T 96=	1.25000E+02
T 100=	1.25000E+02	T 101=	1.25000E+02	T 102=	1.25000E+02
T 44=	1.25000E+02	T 45=	1.25000E+02	T 46=	1.25000E+02
T 50=	1.25000E+02	T 51=	1.25000E+02	T 21=	1.25000E+02
T 25=	1.25000E+02	T 26=	1.25000E+02	T 27=	1.25000E+02
T 31=	1.25000E+02	T 32=	1.25000E+02	T 33=	1.25000E+02
T 37=	1.25000E+02	T 38=	1.25000E+02	T 323=	1.25000E+02
T 6=	1.25000E+02	T 135=	1.25000E+02	T 235=	1.25000E+02
T 152=	1.25000E+02	T 136=	1.25000E+02	T 117=	1.25000E+02
T 130=	1.25000E+02	T 107=	1.25000E+02	T 208=	1.25000E+02
T 223=	1.25000E+02	T 209=	1.25000E+02	T 109=	1.25000E+02
T 133=	1.25000E+02	T 116=	1.25000E+02	T 132=	1.25000E+02
T 134=	1.25000E+02	T 113=	1.25000E+02	T 1=	1.25000E+02

TEMPCC(0)= 0. RELXCC(37)= 9.94878E-01

T 63=	3.11459E+02	T 64=	3.55647E+02	T 65=	3.55647E+02
T 70=	3.15626E+02	T 71=	3.15626E+02	T 72=	3.15626E+02
T 76=	3.37853E+02	T 77=	3.59814E+02	T 125=	2.72869E+02
T 83=	3.04504E+02	T 84=	3.48752E+02	T 85=	3.48752E+02
T 290=	4.56958E+02	T 291=	4.56958E+02	T 294=	3.96711E+02
T 94=	3.23272E+02	T 95=	3.18272E+02	T 96=	4.93284E+02
T 100=	4.37030E+02	T 101=	4.93284E+02	T 102=	3.09521E+02
T 44=	5.18032E+02	T 45=	4.95423E+02	T 46=	4.95423E+02
T 50=	5.18032E+02	T 51=	2.91939E+02	T 21=	2.22044E+02
T 25=	2.32160E+02	T 26=	2.43540E+02	T 27=	2.09147E+02
T 31=	1.84726E+02	T 32=	2.08135E+02	T 33=	2.09147E+02
T 37=	2.93540E+02	T 38=	1.93438E+02	T 323=	1.99008E+02
T 6=	1.83760E+02	T 135=	2.38700E+02	T 235=	2.12102E+02
T 152=	2.40195E+02	T 136=	1.84382E+02	T 117=	1.82206E+02
T 130=	2.36824E+02	T 107=	1.82840E+02	T 208=	1.83020E+02
T 223=	1.81772E+02	T 209=	1.82864E+02	T 109=	1.80365E+02
T 133=	1.75357E+02	T 116=	1.75042E+02	T 132=	1.75037E+02
T 134=	1.82401E+02	T 113=	1.79565E+02	T 1=	1.25000E+02

VII THERMAL MEASUREMENT OF THE ASOC MODULE

After the ASOC module was constructed, a test unit was furnished to the Systems Reliability & Engineering Branch for thermal measurement of the unit. This was necessary since many of the predicted temperatures were much too high to allow a reliable operation of the ASOC module. To accomplish the measurement, the ASOC unit was disassembled and thermocouples were attached to a number of integrated circuit packages. The thermocouples were run through the ASOC module through an opening on the end of the module. These wires were connected to a Hewlett Packard data acquisition system to record and process the data. Once it was hooked up the ASOC module was powered and temperatures were taken until the unit reached thermal steady state. Temperatures of all the IC's were recorded every five minutes. The ASOC module was tested in the ambient laboratory environment (about 70^{o}F). The following contains the measured temperatures of a number of IC's:

TEST RESULTS

Scanner Channel	Thermocouple Location	Measured Temperature(^{o}C)	Δ * (^{o}C)	Field Temperature* (^{o}C)	(^{o}F)
00	Ref Junction	27			
01	Ambient	23			
02	Node 91	50	21	73	163
03	Node 96	44	21	73	163
04	Node 62	44	21	73	163
05	Node 67	41	18	70	158
06	Node 47	57	34	86	187
07	Node 43	47	24	76	169
08	Node 150	47	24	76	169
09	Node 31	36	13	65	149
10	Node 25	42	19	71	160
11	Node 135	42	19	71	160

* Δ = Measured node temperature - measured ambient temperature

* Field Temperature = 52^{o}C + Δ

VIII COMPARISON OF THE PREDICTED AND MEASURED TEMPERATURES

Table 5 shows data that compares the predicted temperatures with the measured temperatures. It also shows how a major source of error impacted the prediction.

The first column shows the node number of the piece part under the heading of the printed circuit board on which it is placed. The second column has the temperature of the piece part that was predicted by the thermal model. The third column has the SINDA prediction that has been modified by a factor to account for electrical stress. The fourth column has the measured temperatures.

The SINDA computer analysis predicted temperatures are off by a large amount, approximately a factor of two for conduction cooled boards and a factor of four for convection cooled boards. During examination of the analysis and discussions with the electrical design engineers, a major source of error was found.

During the thermal analysis, the heat output for each electronic piece part was obtained by multiplying the maximum rated voltage by the maximum rated amperage. This, of course, gave the maximum wattage possible. When the actual power used by the ASOC unit was measured, it was found to be much smaller than the maximum rated power. This produced a large error in the temperature prediction. To eliminate this type of error, the electrical stress should be calculated, then used to calculate the power output for each piece part. In this way, much of the error incurred during an analysis could be avoided. When the predicted temperatures are multiplied by a general power factor, the temperatures of the conductively cooled boards are much closer to the actual temperatures, usually within 40^{o}F. This is about right since the power factor is an average value for the entire ASOC unit and varied for various ASOC units between .4 and .6.

Even with using the correct power output for each IC, the convectively cooled board's temperatures were still off by a factor of two. This shows that the thermal model used for these boards is wrong and should be refined. One of the problems in making these models was the closeness of the boards and the fact that they used conductive cooling through air instead of

the common practice of using metal heat sinks. Because of this, normally used mathematical models (based on empirical data) could not be used directly, and estimations had to be made. This requires considerable experience in using this form of cooling with the given constraints. The errors were on the conservative side and did show up possible problem areas that were then evaluated with thermocouples during the test.

TABLE 5

TEMPERATURE COMPARISON

Item	SINDA Prediction °F	SINDA with Power Correction °F	Measured Temperature °F	Notes
Power Supply				Conduction
135	239	146	160	
6	184	113		
7	184	113		
T/S				Convection
41	254	156		
42	254	156		
43	598	317	169	
44	518	317		
45	495	303		
46	495	303		
47	476	291	187	
48	476	291		
49	476	291		
50	518	317		
51	292	179		
PCM				Conduction
80	305	187		
81	305	187		
82	305	187		
83	305	187		
84	349	214		
85	349	214		
86	349	214		

TABLE 5 (con't)

Item	SINDA Prediction °F	SINDA with Power Correction °F	Measured Temperature °F	Notes
87	349	214		
PTT				Convection
290	457	280		
291	280			
292	397	243		
PCM				Conduction
60	311	190		
61	311	190		
62	311	190	163	
63	311	190		
64	356	218		
65	356	218		
66	356	218		
67	356	218	158	
70	316	193		
71	316	193		
72	316	193		
73	311	193		
74	360	220		
75	360	220		
76	360	220		
77	360	220		
PCM Digit				Convection
91	893	335	163	
92	310	190		
93	306	187		
94	323	198		
95	318	195		
96	493	302	163	

TABLE 5 (con't)

Item	SINDA Prediction °F	SINDA with Power Correction °F	Measured Temperature °F	Notes
97	493	302		
98	443	271		
99	443	271		
100	437	267		
101	310	190		
102	310	190		
Connector				Convection
152	240	147		
151	1996	1222		
150	1996	1222	169	
T/R Board				Conduction
21	222	136		
22	206	126		
23	232	142		
24	244	149		
25	232	126	160	
26	244	149		
27	209	128		
28	208	127		
29	208	127		
30	209	128		
31	185	113	149	
32	208	127		
33	209	128		
34	232	126		
35	244	149		
36	232	126		
37	244	149		
38	194	119		

REFERENCE

1. Military Handbook 251, Reliability/Design Thermal Applications, 1978

a. Pg 484. A minimum thickness for a layer of thermal grease is .005in. since contacting surfaces are not flat, a thickness of .02in. is used.

b. Pg 666. Using a temperature of $60^{o}C$ for the air inside the case, a thermal conductivity of .00075 $\frac{watt}{in^{o}C}$ is obtained after interpolation and unit conversions.

c. Pg 656. Thermal conductivity for copper.

d. Pg 651. For a semi-smooth surface, curve "e" is chosen. Using a contact pressure of 25psi, a value of $.3\frac{in^{2o}C}{watt}$ is obtained for $\frac{1.}{h_c}$

2. Dave S. Steinberg, Cooling Techniques for Electronic Equipment (New York: John Wiley & Sons, 1980), Pg 63.

3. James P. Smith, SINDA User's Manual, (NASA Manned Spacecraft Center: TRW Systems Group, April 1971).

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